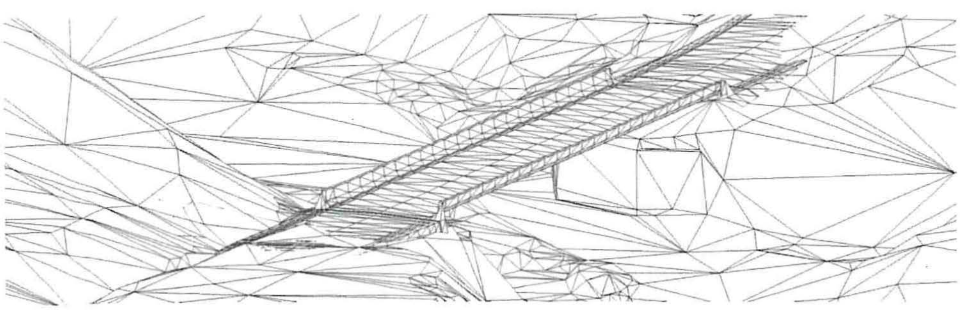
NCHRP

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

SYNTHESIS 560

Practices for Construction-Ready Digital Terrain Models



A Synthesis of Highway Practice

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TRB
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

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The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP SYNTHESIS 560

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ABOUT THE NCHRP SYNTHESIS PROGRAM

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-05, "Synthesis of Information Related to Highway Practices," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, Synthesis of Highway Practice.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

FOREWORD

By Jo Allen Gause
Staff Officer
Transportation Research Board

Digital terrain models (DTMs) are three-dimensional (3D) models of the ground surface showing natural features such as ridges and breaklines. *NCHRP Synthesis 560* documents processes and strategies used by state departments of transportation (DOTs) for the use and transfer of DTMs from design into the construction phase of highway projects.

Information for this study was gathered through a literature review, a survey of state DOTs, and follow-up interviews with selected agencies. Six case examples provide additional information on DOTs' experiences using DTMs during construction.

Gabriel B. Dadi, Hala Nassereddine, Rachel Catchings, Makram Bou Hatoum, and Melanie Piskernik of the University of Kentucky collected and synthesized the information and wrote the report. *NCHRP Synthesis 560* is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Practices for Construction-Ready Digital Terrain Models

Facilitated by advancements in computer-aided design (CAD) technologies, highway designers have had three-dimensional (3D) modeling capabilities for decades. Digital terrain models (DTMs) are 3D models of existing terrain contours created with the input of surveying technologies. DTMs provide a useful reference layer for designers to overlay their proposed work with existing elevations. They also include rich information for contractors. Despite those benefits, departments of transportation (DOTs) have seen inconsistent practices and results from moving these design models to the construction field. This synthesis documents those practices, challenges, and successes across the United States through a national survey and case examples.

The objective of this synthesis study is to document current DOT processes and strategies for the effective use and transfer of DTMs from design into construction of highway projects. Information was gathered from a literature review, survey of DOTs, and follow-up case examples. An electronic survey was created and distributed to the voting DOT members of the AASHTO Committee on Construction, and 40 completed responses were received. Subsequent case example interviews conducted with DOTs in six states provided additional details. Five of those states have significant experience using DTMs in construction, and one state has adopted many e-construction initiatives but has limited experience with DTMs in construction.

Results of the study show that about half of the responding DOTs have been using DTMs for more than 10 years and on more than 50 projects annually. The most common use cases of DTMs were for grade work, quality measurements, and survey verification. Respondents also indicated that they occasionally use DTMs for inspection. DOTs mostly rely on informal peer training, and more than half provide field- and classroom-based training. Half of the responding DOTs use DTMs on all projects regardless of size and mostly for corridor widening, intersection improvements, new or replacement bridge work, and rehabilitation projects. The most common project delivery system for projects that use DTMs is still design-bid-build.

DOTs noted benefits and challenges associated with DTMs. The primary short-term benefits include simplifying the calculation of construction quantities, enabling early identification of plan discrepancies and conflicts, reducing risk during bidding for contractors and DOTs, and improving communication on projects. Long-term benefits include providing cost savings, improving accuracy of plans, improving documentation measurements in databases for future measurement, enhancing communication, improving efficiency of project construction, and reducing claims and litigation. DOTs reported that the major issues for further implementation of DTMs in highway construction include insufficient knowledge or training for inspectors, office staff, and survey staff.

The majority of respondents indicated that DTMs are provided "for information only" for contractors to use at their own risk. Only eight of the responding agencies have used a 3D model as a legal contract document; however, the 3D models do not take precedence over written specifications and two-dimensional plans when conflicts arise. Most DOTs verify their own models by using field verification of survey points, but more than half of DOTs indicated that DTMs are not updated to an as-built condition.

The findings presented in this synthesis are aggregated from 40 different DOTs and provide an overview of the current state of practice of DTMs. Future research could be conducted to expand the scope of work and to survey contractors about their DTM needs and practices. Additionally, as DOTs continue to invest in modeling and sharing information digitally, it becomes critical to further investigate the legal issues associated with using models as contract documents.

CHAPTER 1

Introduction

Digital terrain models (DTMs) are three-dimensional (3D) models of the bare ground surface with natural features such as ridges and breaklines. For highway designers, modeling in 3D with DTMs for visualization and design purposes is not a new capability; however, with the advancement of surveying technology and automated machine guidance (AMG), construction and inspection staff also can leverage DTMs for improved production and efficiency. Despite technological advancements, the handover of DTMs from design to construction has significant inefficiencies for a variety of reasons and remains an inconsistent practice nationally. This NCHRP synthesis documents practices related to that process and to the use of DTMs in construction throughout the United States.

A DTM can represent both the existing terrain condition and the project's as-designed terrain condition. This report references the DTM as the as-designed terrain condition. Occasionally, this report also uses the term "model" or "3D model," which generally refers to the electronic engineering design data in 3D form that would include the DTM. This first chapter of the report provides an overview of the topic, outlines the objective of the synthesis, and describes the study approach.

1.1 Background

Several recent initiatives have specifically sought to push 3D models into the construction phase of projects. For example, FHWA began its Every Day Counts (EDC) program in 2009 as a joint venture between FHWA and AASHTO. EDC focuses on pushing new innovations to accelerate highway project delivery by capturing and sharing case studies and workshops (*1*, *2*). EDC's 2-year cycle starts by securing buy-in from stakeholders and soliciting recommendations on innovations. A baseline evaluation of the innovation is reported, and state and local agencies are tracked for the deployment and use of those innovations. Beyond improving project delivery, another of EDC's goals is to encourage intelligent risk-taking at departments of transportation (DOTs) that may be hesitant to embrace emerging technologies.

EDC Round 2 (EDC-2, 2013–2014) and Round 3 (EDC-3, 2015–2016) involved 3D models in construction. EDC-2 encouraged "3D Engineered Models for Construction" (*3*). EDC-3 drilled down to a topic of "3D Engineered Models: Schedule, Cost, and Post-Construction" (*4*).

EDC-2 found primary benefits in improved project delivery, improved communication, enhanced identification of errors, and improved visualization (*3*). Specific benefits were identified by various stakeholders as well. For agencies, 3D models allowed for random grade checks at specified cross-sections, realization of material cost savings, and easier identification of quality assurance (QA) test locations. For contractors, the primary benefits included labor

savings (through elimination of staking and stringlines), increased productivity, fewer conflicts, and fewer changes. Consultants benefited from early identification of constructability concerns, improved design accuracy, and improved visual verification for quality control (QC). Overall, FHWA identified 66% savings in grade checking, 85% reduction in stakes, 3%–6% improved material yields, and 30%–50% reduction in earthwork interruptions (*3*). Ultimately, total project cost savings of 4%–6% were found (*3*).

The focus in 2015 and 2016 was on integrating cost, schedule, and post-construction data (survey, as-built, and other asset management data) into the 3D models through EDC-3. The benefits found include improved project management, more accurate cost estimates, and a living record throughout the project life cycle (*4*). FHWA captured case studies from the California, Washington state, and Massachusetts DOTs to identify these benefits. Ultimately, the final report from EDC-3 published data on the degree of implementation for 3D models used in planning, design, and construction, as seen in Figure 1 (*5*). There were significant improvements in adoption from the baseline in January 2015 to the end of the EDC round in December of 2016; however, it is not clear if that adoption was strictly the 3D design file used or if it included the existing terrain captured in a DTM. This report can bridge that knowledge gap by identifying the state of practice of DTM use in the construction phase of highway projects.

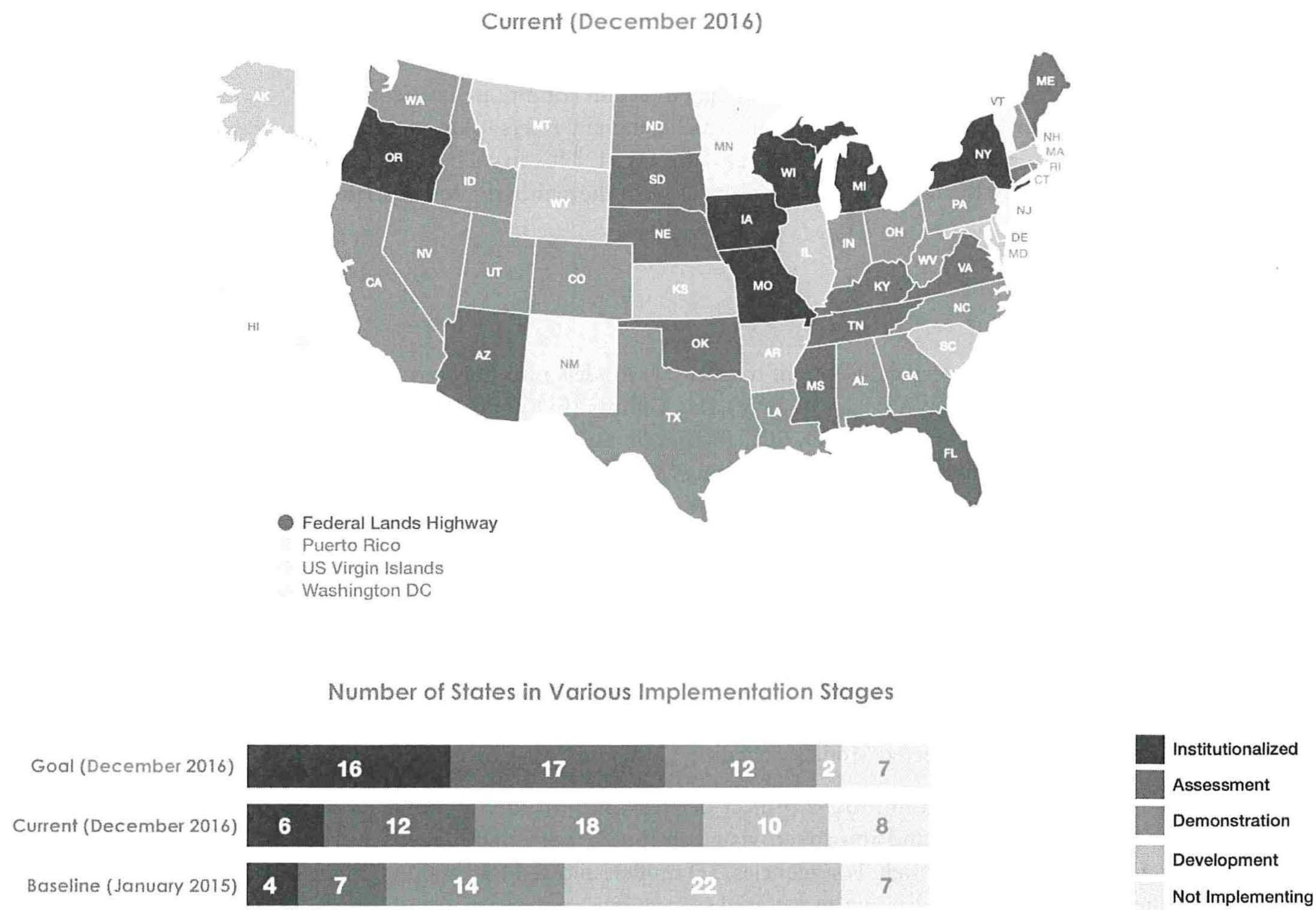


Figure 1. FHWA EDC-3 baseline and goal for 3D models in planning, design, and construction (5).

1.2 Synthesis Objective

This synthesis seeks to gather state-of-practice information regarding the current processes and strategies for effective use and transfer of DTMs from design into the construction phase of highway projects. DTMs have significant potential to improve the accuracy and efficiency of construction and inspection operations, yet little research exists to detail practices and performance. The purpose of this synthesis is to document and identify DOTs that have experience using DTMs in construction and to provide an overview of implementation to date and of lessons learned, identifying success factors and challenges. Specifically, this synthesis collected the following information regarding the use of DTMs in highway construction:

- Extent of DOT use of DTMs for construction and inspection
- Size and type of projects using DTMs for construction (e.g., new construction, rehabilitation, maintenance)
- Existence of written DOT guidance for the use of DTMs in design and construction phases
- Whether DTMs are considered legal documents and, if so, the extent of liability for accuracy and level of detail
- How DOTs ensure that the contractor's DTM is equivalent to the designer's DTM
- Whether DTMs are provided to contractors for "information only" during the letting process
- Responsibility for DTM model modifications during construction (e.g., DOT staff, consultants, contractors)
- DOT process for quality control and assurance
- Benefits of and challenges to effective use of DTMs in construction

1.3 Study Approach

An extensive literature review on the topic provided the initial understanding on the current state of research and practice regarding 3D modeling and DTM use in highway construction. The existing literature and previous discussions with DOTs assisted with the development of the survey questionnaire.

A survey was created to capture the state of practice of DTMs within DOTs. Under the guidance of the topic panel, the survey was divided into the following categories: Demographic Information, General DTM Use, Project-Specific DTM Use, User/Non-User Experience Feedback, Legal Issues, and Designer/Contractor Interface. Qualtrics provided the platform for the creation and distribution of the electronic survey. Once the final draft of the survey was approved, an email request with the survey link was distributed to the voting DOT members of the AASHTO Committee on Construction. At the time of survey distribution, this constituted voting members from each of the 50 U.S. states as well as the District of Columbia. The committee members were asked to distribute the survey to individuals with knowledge of DTM use within their organizations. The complete survey questionnaire is shown in Appendix A with aggregate results presented in Appendix B.

Forty responses were collected from the survey. This sample represents participation by 40 different DOTs, providing an 80% response rate from the 50 state DOTs. The map in Figure 2 shows the states that responded to the survey.

Following the analysis of survey responses, subsequent case examples were conducted to gather further information on the topic. Because DTM use in construction is widespread but inconsistent nationally, a strategy was needed to select the states for the case examples. The selection criteria included DOTs' experience with DTMs, the number of projects that have used DTMS, and the use of DTMs as part of contract documents. Six states were chosen for the

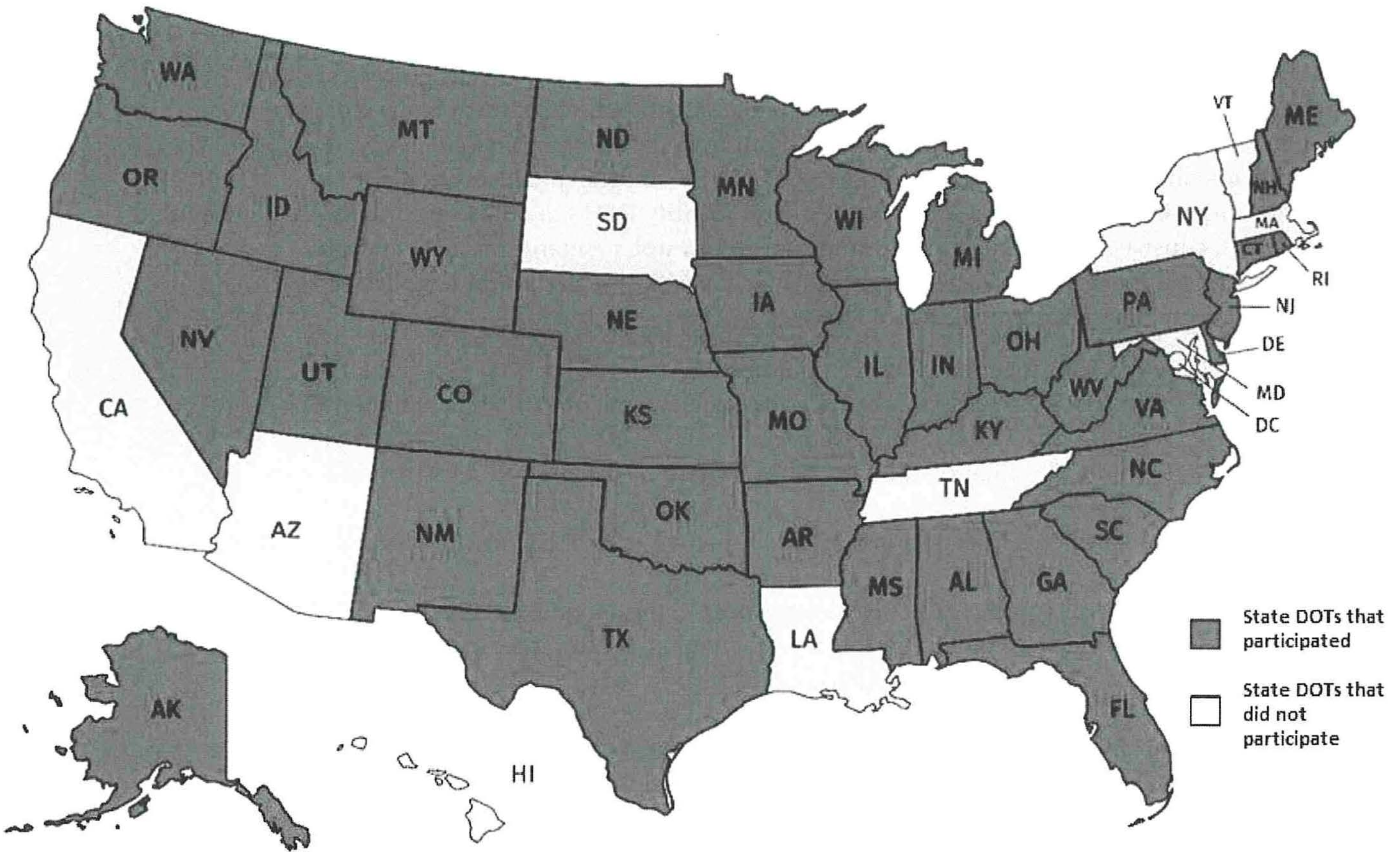


Figure 2. Map of DOTs responding to survey.

examples to provide an in-depth understanding of the successes, challenges, and barriers to using DTMs in construction. Five of the chosen states had significant experience, both in time and number of projects, with DTMs. One state was specifically targeted for its initiatives related to e-construction despite its limited experience with DTMs. The states were contacted for assistance with the study, and all six agreed to participate in the interviews. Details of the individual case examples are outlined in Chapter 4, and the questions asked during the interviews can be found in Appendix C.

CHAPTER 2

Literature Review

This review focuses on previously published academic literature on DTMs and their use. However, little documented knowledge exists in this domain, especially related to the use of DTMs in construction. Thus, the review begins with an introduction to DTMs, the technology used to create DTMs, the use of 3D models in construction, and similar products in the building construction sector. A higher-level overview of construction use of 3D models in the U.S. highway construction industry can be found in the background section of the Introduction.

2.1 Digital Terrain Models

Because many engineering problems require accurate representations of the Earth's surface, solutions have been developed to efficiently transform terrain data into models—such as DTMs—that can be analyzed by computers. DTMs are continuous representations of the ground surface and are generated using "a large number of selected points with known XYZ coordinates in an arbitrary coordinate field" (*6*). These points are used to produce a 3D model that can be analyzed with the help of computer algorithms. Generally, these models capture landform characteristics (e.g., elevation, slope), terrain features (including hydrographic and transportation networks), and natural resources.

2.2 Reality Capture Technologies for Creating DTMs

DTMs are constructed using data acquired via remote sensing technologies such as LiDAR, 3D laser scanning, and georeferenced point clouds with high-resolution imagery. Gant and Boivin summarized the data acquisition process for generating DTMs, as shown in Figure 3 (*7*). Using remote sensing technology carries several benefits, including time and cost savings, less rework, increased productivity, enhanced bidding quality, and fewer safety incidents (*8*).

It is estimated that more than half of state DOTs were using some type of LiDAR technology back in 2013 (*3*). Common LiDAR data collection technologies include (1) airborne or aerial LiDAR, which uses airplanes or drones, GPS devices, and inertial measurement units (IMUs); (2) terrestrial mobile systems or mobile laser scanning (MLS), which uses moving vehicles, multiple 3D scanners, positioning hardware, cameras, data acquisition systems, and computer monitors for shoulder-to-shoulder highway corridor mapping; and (3) static laser scanning, which uses scanners and cameras mounted on tripods to survey highway structures like bridges and tunnels.

Most researchers have found that these latest technologies outperform traditional surveying methods. A study comparing MLS technology to traditional surveying on an Iowa DOT interchange project confirmed the accuracy, safety, and efficiency benefits of MLS (*9*). Additionally,

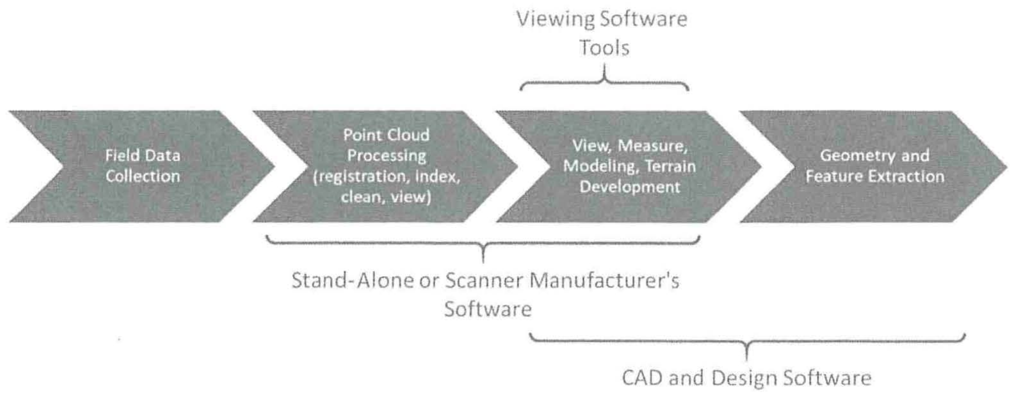


Figure 3. Point cloud processing pipeline [Reproduced from Gant and Boivin (7)].

the Alabama DOT investigated potential benefits of the use of MLS, including increased safety, time savings, and increased level of detail, accuracy, and scalability (*10*). Another study, performed in conjunction with the North Carolina DOT, outlined guidance for how DOTs can determine whether LiDAR can be practically used by transportation agencies; it specifically examined different aspects and performance measures for effectively deploying LiDAR equipment or taking advantage of contracted services (*11*). The Utah DOT found that using LiDAR data with supplemental surveying methods resulted in cost savings of 24% and time savings of 22% as compared to using traditional surveying methods alone (*12*).

Researchers surveyed 50 DOTs, six transportation agencies, and 14 MLS service providers on the adoption of MLS (*13*). They found that a main reason DOTs have not used MLS more widely is that they want to see more evidence of its benefits validated through cost–benefit studies (*13*). A cost–benefit analysis of Washington DOT and Caltrans projects that used MLS showed that the agencies enjoyed millions of dollars in savings as well as intangible benefits related to the environment, people, and traffic (*14*). Another study provided guidelines for using MLS in transportation applications; incorporating tasks from project planning, design, and construction to operations and maintenance; and addressing data collection methods, formatting and management, storage requirements, QA, and translation and formatting of derived products (*15*).

2.3 3D Models in Highway Construction

State DOTs have increasingly turned to 3D models in their construction projects. These models can help automate highway construction and are essential for stakeholder communication and coordination on large transportation projects, on which multiple design, construction, and consultant teams must work together (*16*). The shift from two-dimensional (2D) plans to 3D models was mainly driven by contractors using AMG and having to reengineer 3D models from 2D plans, which is a burdensome and time-consuming task (Figure 4) (*17*). Recognizing the importance of 3D models in all phases of a highway project, including planning, design, maintenance, and operations, contractors are now using 3D models for bid preparation (e.g., more accurate earthwork quantities), clash detection, and field inspection (*8*).

During the project design phase, shifting from 2D to 3D models has brought numerous challenges, such as an increase in cost and time to generate designs; a lack of standards, which results in incompatibility issues due to different modeling technologies; problems related to data management privacy and errors; the need for training expertise (especially on software); lack of guidelines and specifications for 3D designs (such as error tolerance and level of

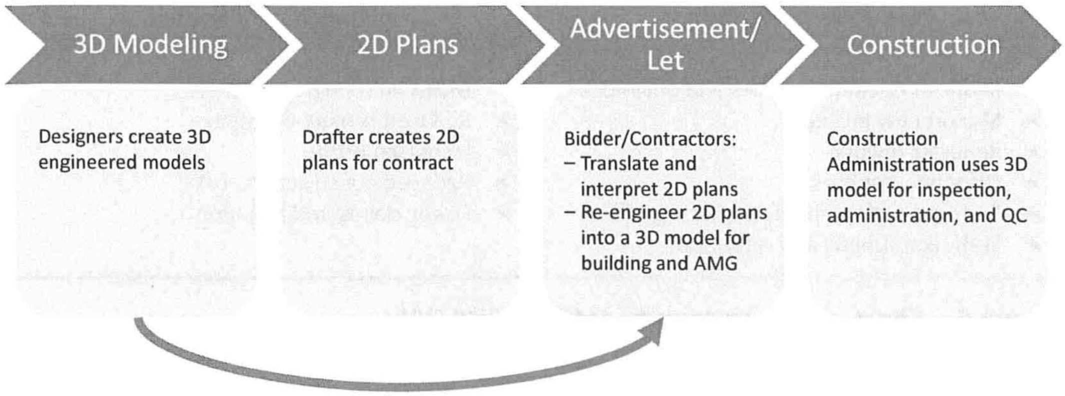


Figure 4. Comparison of 2D and 3D design workflows [Reproduced from Arena (17)].

detail); issues with model validation; and contractual issues, especially at the level of 2D versus 3D model deliverables (*8*). Nonetheless, the benefits of 3D models outweigh their drawbacks. These benefits include cost and time savings and increased productivity. The report also noted that various DOTs have forged ahead with 3D modeling and have aggressively moved to resolve the challenges mentioned (*8*). For instance, the Wisconsin DOT began developing 3D design models for large projects, justifying the costs by noting that staff members would gain experience they could then apply on smaller projects. The agency has also conducted review sessions on 3D models with designers, consultants, construction professionals, and industry personnel for model validations. Elsewhere, the Iowa DOT has dedicated information technology (IT) staff during the design phase to support 3D design efforts; the Oregon DOT has established guidelines for determining the increased tolerances and level of detail required for 3D design (by surveyors, designers, and project managers) and also allocates extra time for 3D modeling in project schedules and reviews and performs quality checks and assurances on digital files. Agencies handle training individually because it presents a challenge that requires significant organizational and cultural changes. DOTs have invested in pilot projects to demonstrate the advantages and benefits of 3D design, partnered with consultants and software developers, and formed leadership teams to guide transitions (*8*).

An FHWA report on the use of 3D digital design data in highway construction found that leveraging 3D data creates opportunities and challenges with respect to risk allocation, enterprise data management, workforce development, and industry-related matters (*18*). Looking at six projects, the study found that all construction parties benefited from 3D drawings, with resident engineers and inspectors being the most affected. Given appropriate training, resident engineers viewed 3D drawings as a safer and more efficient method for real-time verification and an easier way to measure payment quantities from post-construction drawings. Inspectors could also document inspections in a more accurate and transparent manner.

2.4 Building Information Modeling for Infrastructure

As DTMs have gained momentum in the highway sector, the building sector has further advanced 3D modeling through building information modeling (BIM). BIM has upended construction industry paradigms through the shift from 2D-based drawing information systems to 3D object-based information systems. BIM can also model beyond three dimensions, with 4D (time), 5D (cost), and 6D (as-built operations) modeling as options. It establishes a shared knowledge resource for information on a facility, forming a reliable basis for decisions during its life cycle, from inception to commission and beyond. For instance, a recent study divided BIM

Short-Term Benefits	Long-Term Benefits
➢ Reduced document errors and omissions	➢ Maintain repeated business
➢ Market new business	➢ Reduced project duration
➢ Reduced rework	➢ Increased profit
➢ Offer new services	➢ Reduced construction cost
➢ Reduced cycle time of specific workflows	➢ Fewer claims and litigation
➢ Staff recruitment and retention	

***Figure 5. Short- and long-term benefits of BIM* (20).**

applications into three project phases: pre-construction, construction, and post-construction (*19*). During pre-construction, BIM serves as an early collaboration platform for sharing information and using 3D models for estimating takeoffs. During construction, BIM can be used to keep track of schedules, cash flows, and work progress in real time to reduce work and overruns. Additionally, BIM enables the creation of digital as-builts, which can be used further on in the project life cycle.

Widely acknowledged as a successful innovation in the construction industry, BIM has been studied by construction researchers to identify its benefits. In 2012, McGraw-Hill Construction surveyed construction professionals to identify the short- and long-term benefits of using BIM (*20*). These benefits are listed in Figure 5. The study also highlighted the business benefits of major construction project stakeholders, especially the impact of BIM on architects, engineers, contractors, and owners. An international survey verified previous findings of BIM benefits in efficiency and process, performance and knowledge, sustainable building, technical aspects, finances, and legal-related matters (*21*). Most of the survey respondents felt that BIM enhances overall project quality as well as productivity and efficiency.

With the growing success of BIM in the vertical construction industry, BIM for infrastructure (BIMfI) is also finding success in Europe and Asia as an asset life cycle management methodology. Consequently, BIMfI has garnered increased interest in the United States and within DOTs (*22*). FHWA defines BIMfI as "a collaborative work method for structuring, managing, and using data and information about transportation assets throughout their life cycle" (*23*). AASHTO and FHWA are working with buildingSMART International to establish open standards for the exchange of data. buildingSMART International is the body overseeing the development of Industry Foundation Classes (IFC) standards, which are platform-neutral, open standards for the exchange of building and construction industry data. AASHTO's Joint Technical Committee on Electronic Engineering Standards has formally adopted the use of IFC. This partnership aims to develop the IFC Bridge Design to Construction Information Exchange to develop standards for bridge information modeling and related data exchange protocols (*24*). DTMs are a key element of BIMfI because they serve as the baseline 3D environment for developing the BIM model (*25*).

CHAPTER 3

State of Practice

As noted in Chapter 1, an online survey questionnaire was built in Qualtrics and distributed by email to members of the AASHTO Committee on Construction (COC). Forty responses across 40 DOTs were received (Figure 6). Appendix B contains the aggregate survey results collected in Qualtrics. It also presents partially completed responses not included in the analysis in this chapter because of the lack of information provided. This chapter reports on results from key survey questions.

Respondents were asked to identify the division in which they work and their corresponding role. As seen in Figure 7 and Figure 8, half of the respondents work in the construction division (50%) with a designated role of construction engineer or engineer manager (48%). Given that the survey was distributed to the AASHTO COC, this is not a surprising result. Survey recipients were asked, however, to distribute the survey to the individual in the DOT most knowledgeable of their processes for preparing and using DTMs in construction. With that request, 18% of survey respondents work in highway design, 18% work in computer-aided design and drafting (CADD)/support, 8% work in surveying support, and the remaining 8% self-designated as "other." Figure 7 shows that respondents who selected "other" worked in more than one division specified in the survey, whereas Figure 8 shows that those who selected "other" had roles in administration technology implementation, design fields, and surveying.

The survey consisted of five sections covering general DTM use, project-specific DTM use, user/non-user experience feedback, legal aspects, and designer/contractor interface. Each section of the survey, along with its results, is described in detail in this chapter.

3.1 General DTM Use

This section covers the technical aspect of DTM at the DOT, uses in construction-phase applications, developer and end-user training, years of use, and maturity level of models.

3.1.1 DTM Usage Frequency

Respondents were asked to indicate the number of projects that use DTM in a year. Only 15% of the surveyed DOTs indicated that DTM is used on fewer than 10 projects annually. Thirty-eight percent of the respondents reported that their DOT uses DTMs on 10 to 50 projects, 23% mentioned the use of DTM on 50 to 100 projects, and 25% indicated that they use DTM for more than 100 projects. Figure 9 depicts the DTM usage frequency of the 40 responding DOTs.

3.1.2 DTM Usage Timeline

To capture how long DTMs have been used, respondents were asked to estimate the number of years their DOT has been using DTMs in the construction phase of projects. Results show

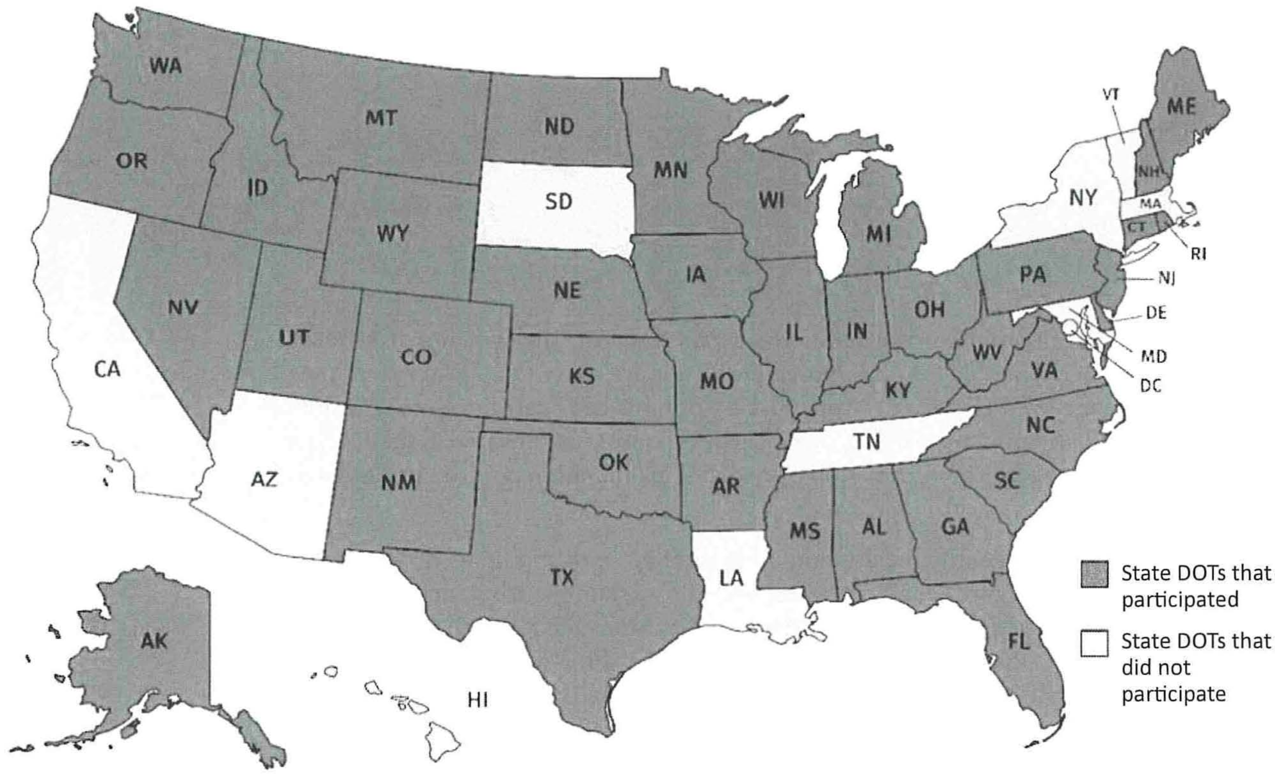
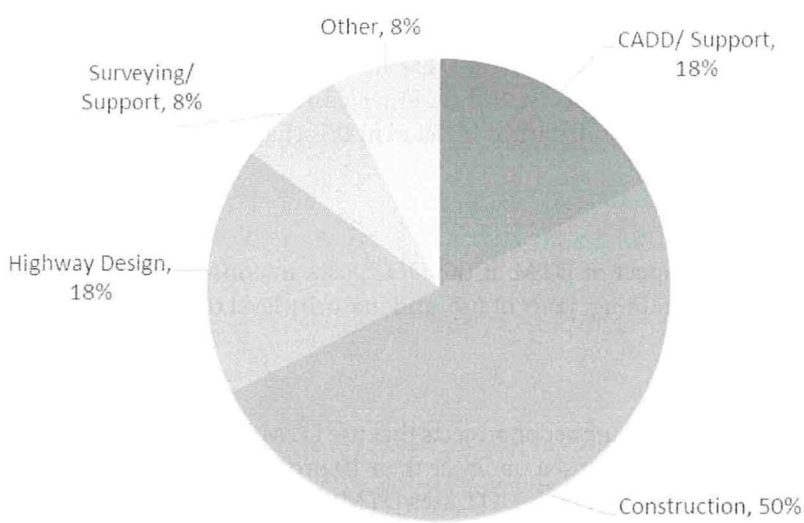
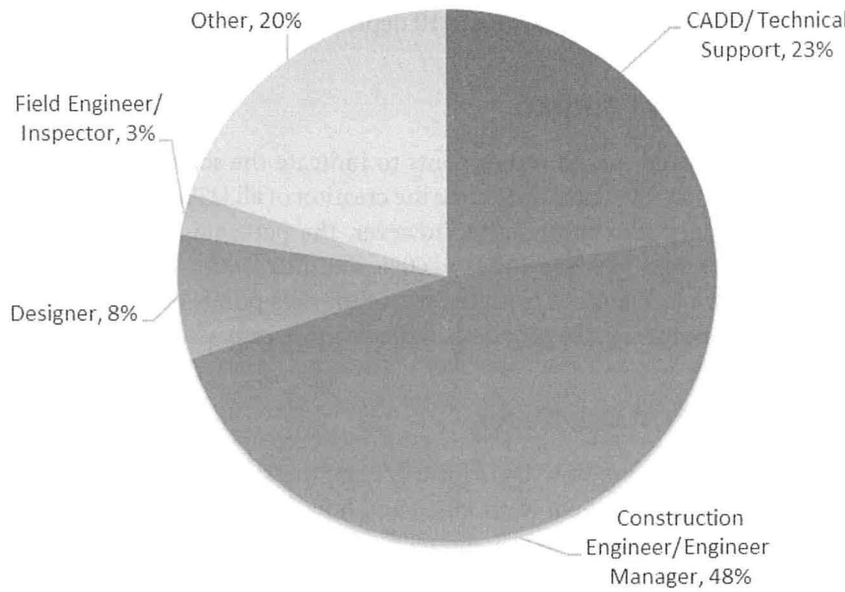


Figure 6. Map of DOTs responding to the survey, N = 40.



Note: Numbers do not add to 100% because of rounding.

Figure 7. Distribution of the division of respondents in their DOTs, N = 40.



Note: Numbers do not add to 100% because of rounding.

Figure 8. Distribution of the role of respondents in their DOTs, N = 40.

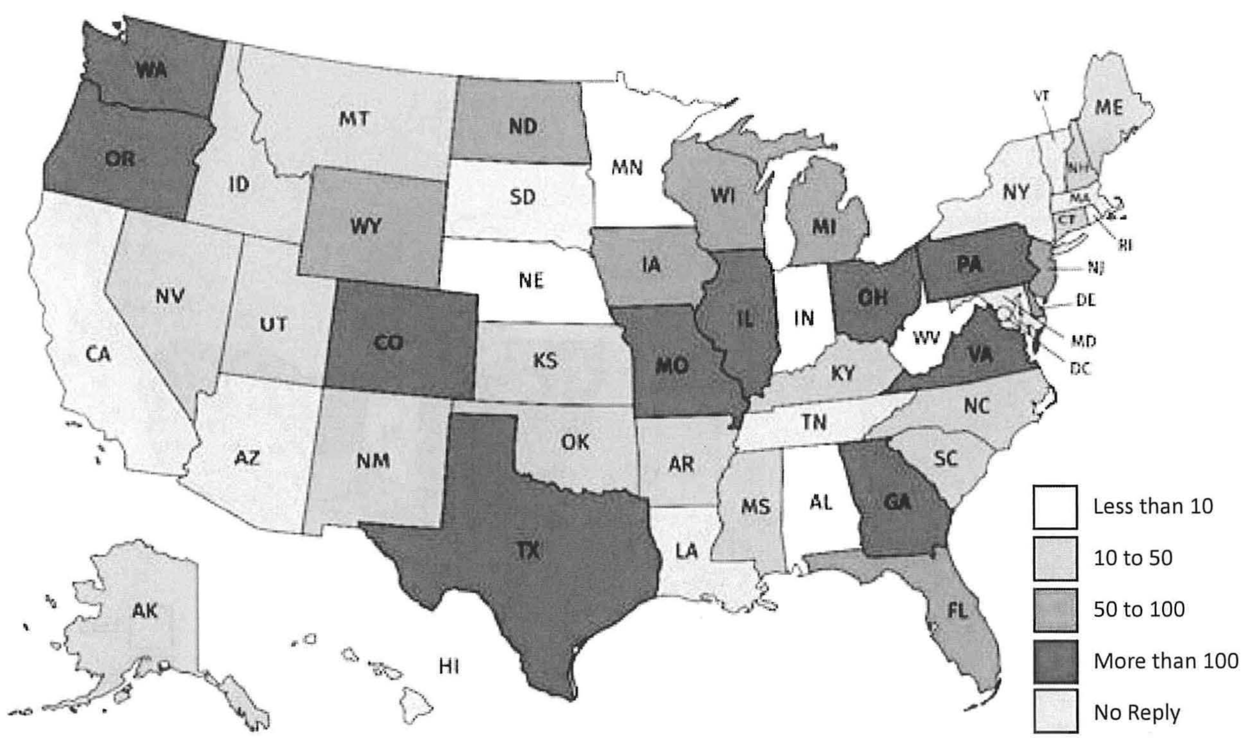


Figure 9. Breakdown of DTM usage frequency (by number of projects) per state, N = 40.

that 11% of the DOTs have been using DTMs for less than 3 years, 16% of the responding DOTs have between 3 and 7 years of experience using DTMs, 29% reported experience of 7 to 10 years using DTMs, and 45% of the respondents indicated that their DOT has been using DTMs for more than 10 years. Figure 10 depicts the DTM usage timeline of the 40 responding DOTs.

3.1.3 DTM Source

The survey asked respondents to indicate the source of DTMs used in their construction projects. A few states outsource the creation of all DTMs, whereas a few create all models within the agency. For most states, however, the percentage of outsourced or in-house-developed DTMs ranges between 40% and 60%. The distribution of the results as indicated by respondents is shown in Figure 11, with the size of the data points being relative to the number of responses at that point (i.e., larger circles indicate more responses).

3.1.4 DTM Use Cases

To determine how DOTs use DTMs, the survey provided respondents with 11 DTM use cases and asked them to specify if and how frequently their DOT practices each one. As shown in Figure 12, between 5% and 69% of respondents mentioned that their DOT does not use a particular DTM use case. The rest of the respondents (i.e., between 30% and 95%) indicated that a particular DTM use case is used by their DOT.

Respondents whose DOT practiced a DTM use case rated the frequency on a scale of rarely, sometimes, often, and always. Figure 13 summarizes the results of the distribution of the respondents' frequency of DTM usage and shows that DTMs are most commonly used for Grade Work (UC1), Automated Machine Guidance (UC5), and Survey Verification (UC3).

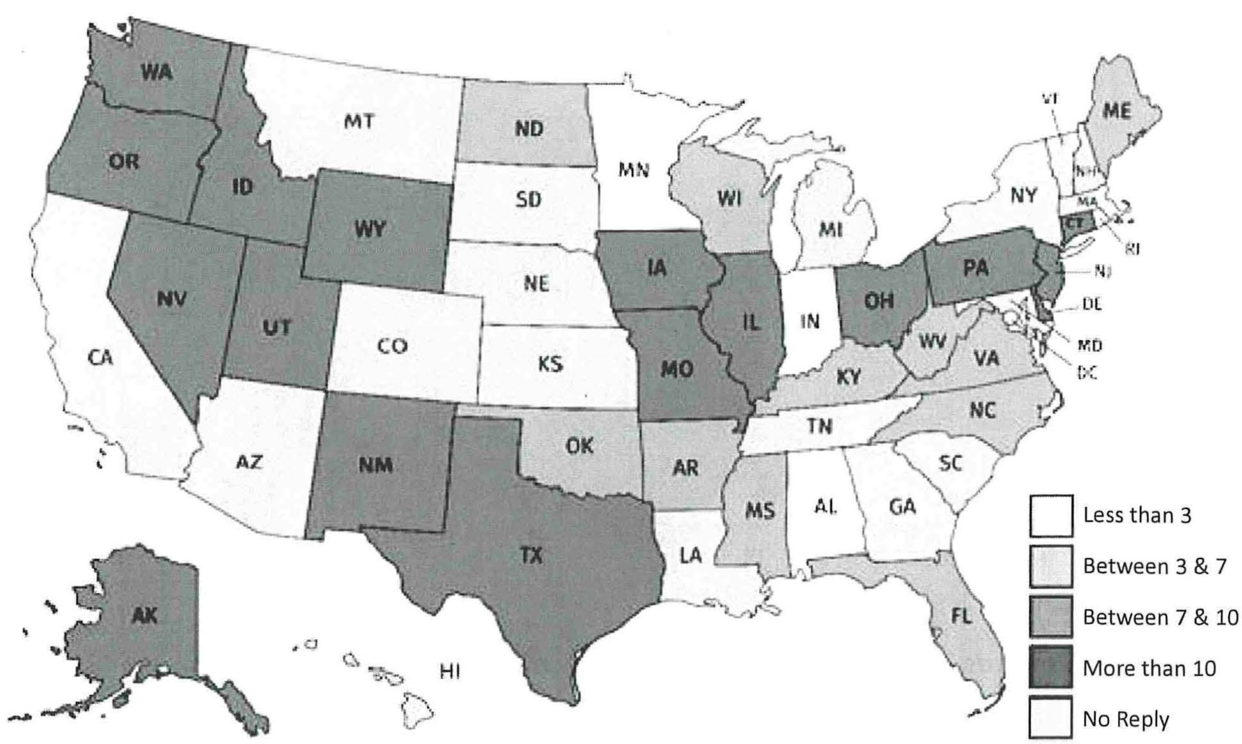


Figure 10. Breakdown of DTM usage timeline (in years) per state, N = 40.

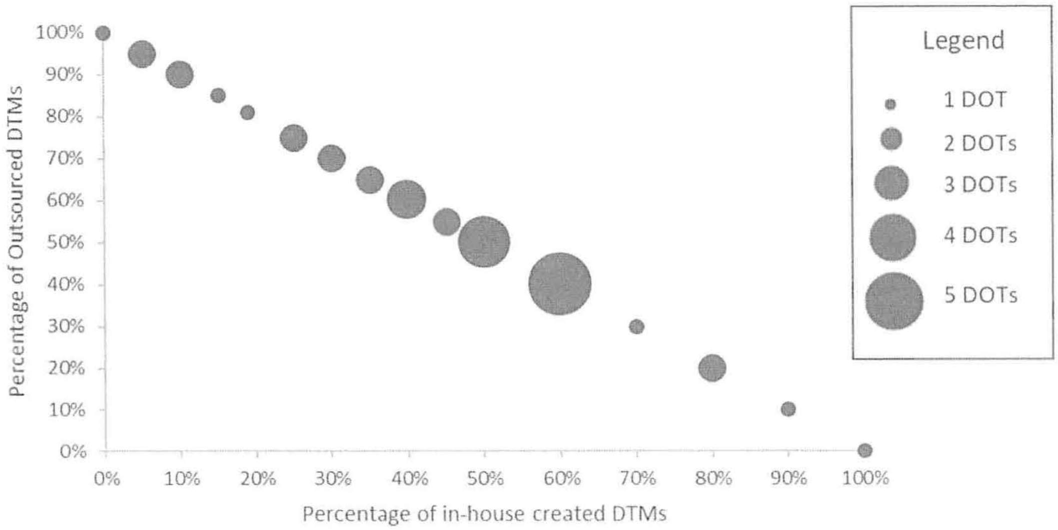
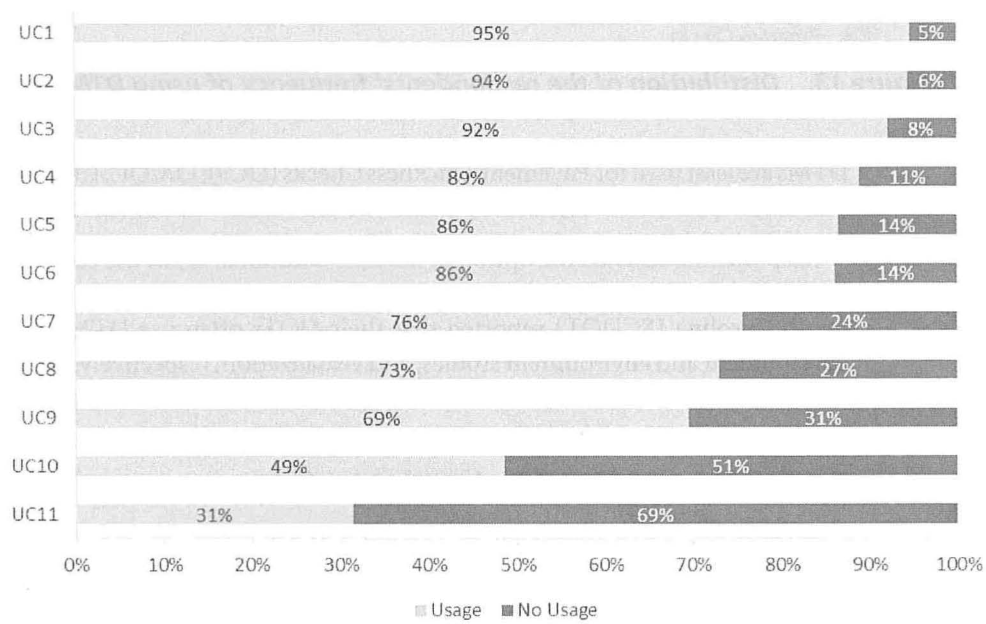


Figure 11. ***Variation in the sources of DTM across DOTs, N = 32.***



UC1 Grade Work
UC2 Quality Measurements
UC3 Survey Verification
UC4 Field Staking
UC5 Automated Machine Guidance
UC6 Progress Checks
UC7 Cost Analysis for Initial Construction Bid
UC8 QA/QC, Clash Detection, or Reducing Plan Discrepancies
UC9 Pavement Thickness Checks
UC10 Work Planning Productivity, or Efficiency
UC11 Cost Analysis for Future Maintenance

Figure 12. ***DOT responses on the different use cases of DTM, N = 38.***

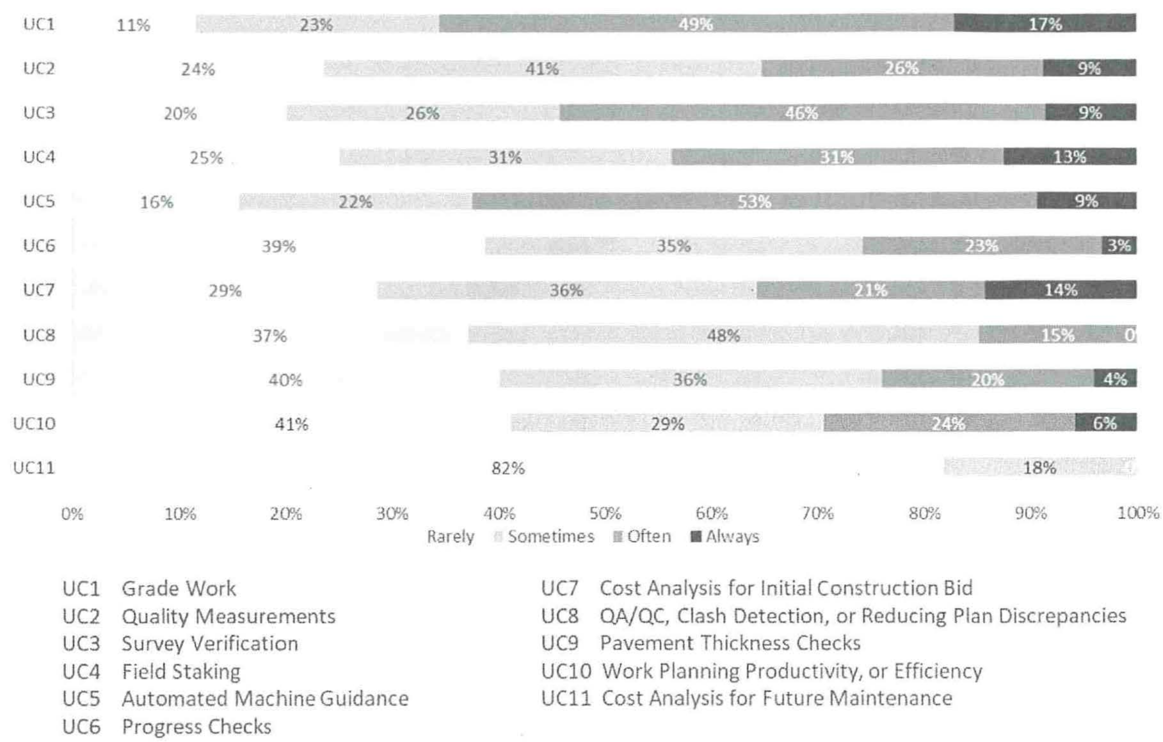


Figure 13. Distribution of the respondents' frequency of using DTM, N = 38.

DTMs are least used for Pavement Thickness Checks (UC9); QA/QC, Class Detection, or Reducing Plan Discrepancies (UC8); and Cost Analysis for Future Maintenance (UC11).

Respondents also had the option to indicate additional DTM use cases that were not included in the survey. Respondents from the DOT in Pennsylvania (PennDOT), Florida (FDOT), and South Carolina (SCDOT) reported that their DOTs often use DTMs for design, production development and environment studies, and visualization, respectively. On rare occasions, FDOT also uses DTMs for construction sequencing, and SCDOT uses the models for hydraulic design.

3.1.5 DTM and Construction Inspection

Because the use of DTMs can be extended to inspection, survey respondents were asked to indicate how frequently their DOT uses DTMs in construction inspection processes. As illustrated in Figure 14, only 10% of the respondents said that DTMs were not used for inspection, 24% of the respondents indicated a rare usage of DTMs in the construction inspection process, another 42% reported that a DTM is sometimes used for inspection, and 24% mentioned that their DOT often uses a DTM for inspection.

3.1.6 DTM Training Provided to Construction Inspection Staff

The survey investigated the type of DTM training that was provided to construction inspection staff. The results illustrated in Figure 15 show that the majority of the surveyed DOTs (84%) provide informal peer training. Field-based and classroom-based training on hardware and software are also common types of DTM training provided by 65% and 52% of the responding DOTs, respectively. Fewer respondents (32%) reported that their DOT only provides reference material. Ten percent of the surveyed DOTs do not provide any DTM training to construction inspection staff.

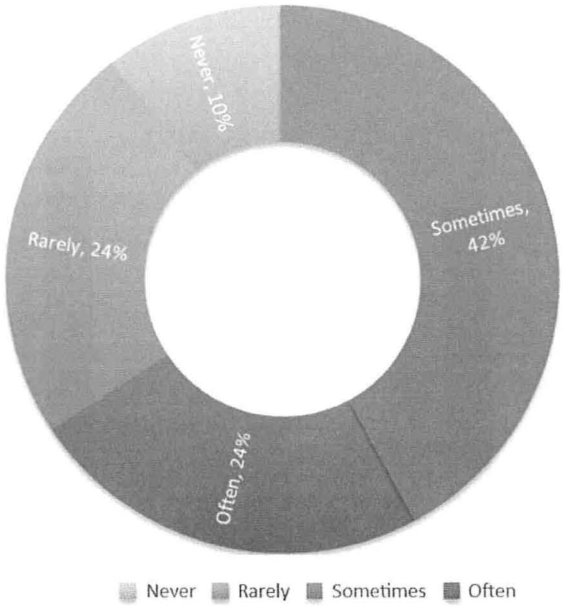


Figure 14. Frequency of DTM use for construction inspection, N = 38.

Respondents also had the option to report other types of training that were not listed in the survey. One respondent indicated reliance by the DOT on the training provided by a contractor or vendor when using GPS rovers for earthwork quantity checks.

3.1.7 DTM Handover

To assess the readiness of DTMs handed over to contractors, the survey asked respondents to evaluate different aspects of these DTMs using a five-point Likert scale of very low (1), low (2), moderate (3), high (4), and very high (5). Respondents were asked to evaluate each aspect from two perspectives: (1) from the perspective of their DOT and (2) from the perspective of contractors as perceived by the DOT. The reasoning for this approach is that the researchers wanted to grasp not only the levels of quality and usefulness of the models

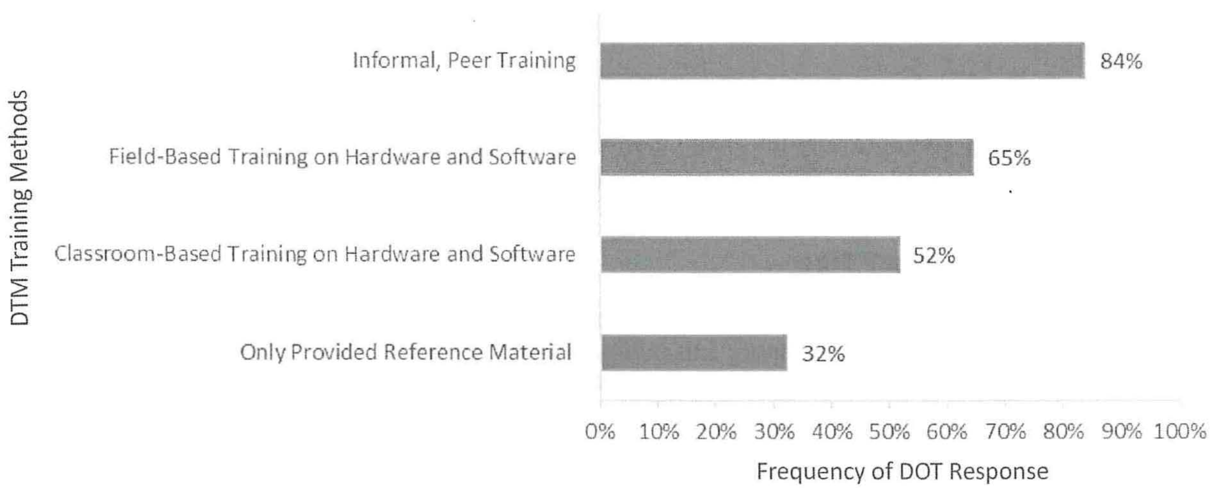
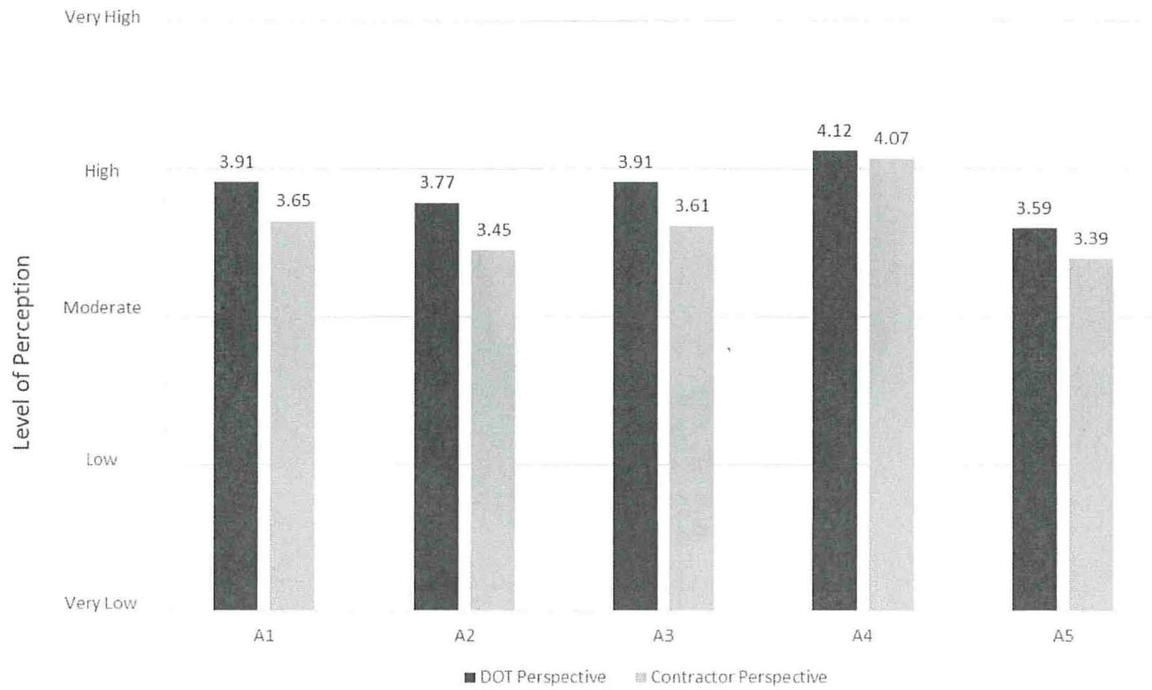


Figure 15. End-user DTM training methods, N = 37.



A1 Accuracy Compared to PDF/Printed (Contract) Plan Information
A2 Interoperable Format (or Usefulness of Data Format)
A3 Level of Detail (Level of Precision Between the Model's 3D Geometry and Real World)
A4 Overall Usefulness
A5 Quality or Completeness

Note: Respondents used the following scale: Very Low = 1, Low = 2, Moderate = 3, High = 4, and Very High = 5.

Figure 16. Respondents' evaluation of DTM aspects as perceived by DOTs and contractors (from the DOT perspective), N = 33.

that the DOTs created or received from designers but also the levels of quality and usefulness of the models according to the contractors. Given that the survey is distributed to DOT personnel, the question had to be posed as seeking the perspective of the contractors as perceived by the agency. On average, all five aspects of DTMs that are handed over to contractors to use are reported to be moderately to highly acceptable from both perspectives, as shown in Figure 16.

3.2 Project-Specific DTM Use

This section provides information on highway construction projects that use DTMs. It covers project size and type, delivery systems used, and the party responsible for construction inspection.

3.2.1 Project Size

Respondents were asked to indicate the size of projects on which DTMs were used. As seen in Figure 17, 51% of the respondents indicated that their DOT uses DTMs for all projects regardless of size. Other respondents reported that they use DTMs for specific project sizes (Figure 17). Respondents had the option to select multiple categories of project sizes that apply to their DOTs. DOTs that do not use DTMs on all projects use DTMs mostly on larger projects with sizes exceeding $5 million. A small percentage of DOTs (5%) uses DTMs for small projects that are less than $1 million.

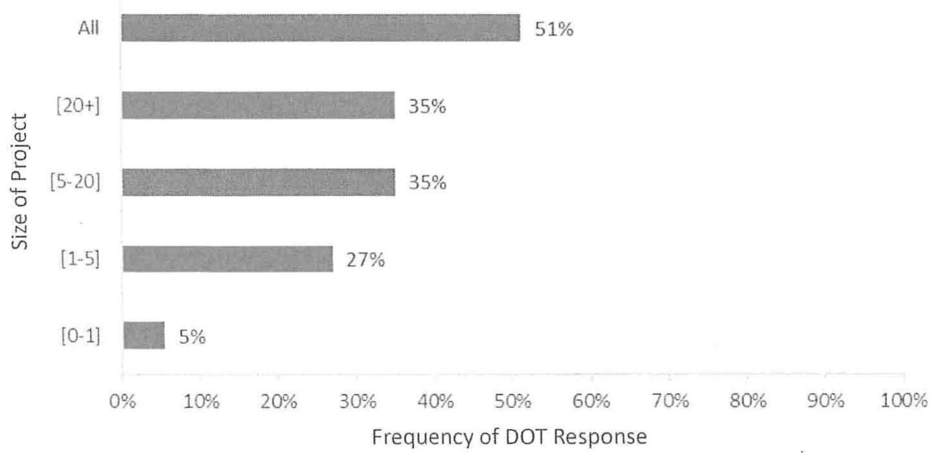


Figure 17. DTM use relative to project size (in $ millions), N = 37.

3.2.2 Project Type

Respondents were asked to identify the types of projects for which their DOT uses DTMs. As illustrated in Figure 18, most responding DOTs use DTMs for widening corridors (87%), improving intersections (79%), replacing or constructing new bridges (71%), and rehabilitating roads (68%). DTMs are least used for road resurfacing (26%), bridge rehabilitation (37%), and safety improvement works such as shoulder widening, rumble strips, pavement marking/markers, and guardrail projects with minimal design (39%).

3.2.3 Project Delivery System

As shown in Figure 19, respondents indicated that DTMs were mostly used with the traditional design-bid-build delivery method (91%) and least used with public-private partnerships (11%). There is moderate use of DTMs with the design-build (DB) and construction management/general contractor (CM/GC) delivery methods at 54% and 29%, respectively. In the case example

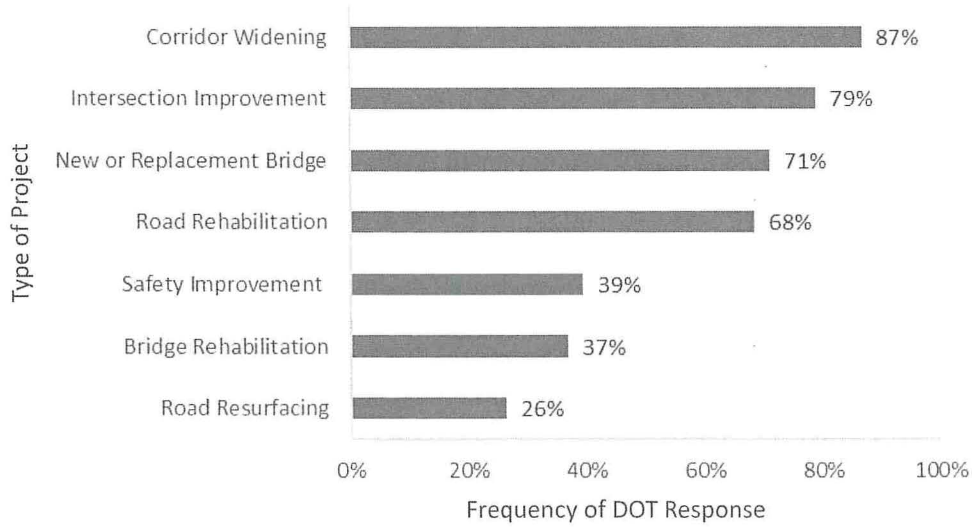


Figure 18. Use of DTMs by project type, N = 37.

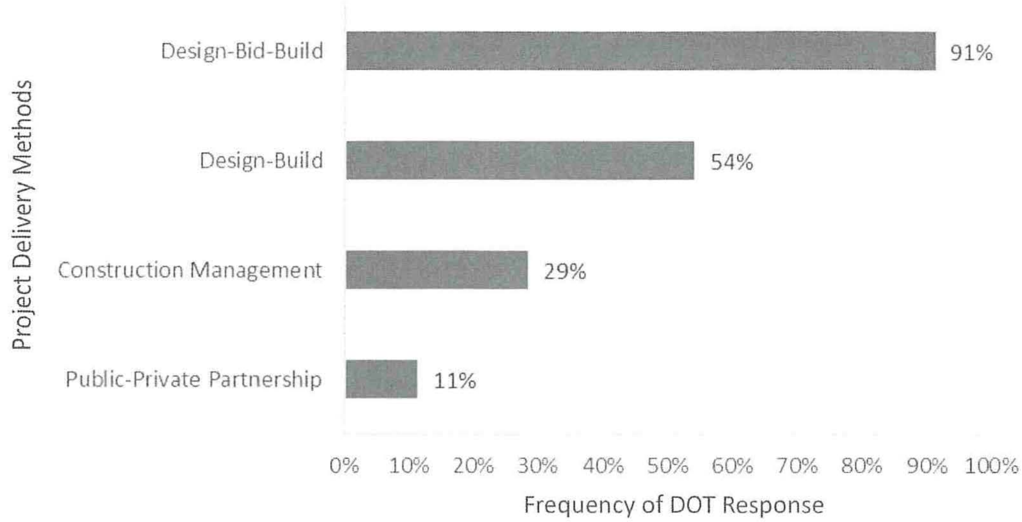


Figure 19. DTM usage relative to project delivery methods, N = 35.

discussions in Chapter 4, states note that DB and CM/GC, in particular, enable better DTM use in construction, given the ability to have early contractor involvement.

3.2.4 DTM Construction Inspection

Respondents were asked to specify the party responsible for construction inspection on projects that used DTMs. Of the 36 respondents answering this question, 42% indicated that DOT staff members were responsible for construction inspection, 14% mentioned that construction and engineering inspection (CEI) consultants were responsible for construction inspection, and the remaining 44% said that both DOT staff members and CEI consultants were responsible.

3.3 User/Non-User Experience Feedback

This section reports respondents' perceptions of the benefits associated with DTM use and the barriers impeding its adoption, and summarizes their experience with DTMs.

3.3.1 DTM Project-Specific Benefits

Respondents were provided with a list of six project-specific benefits for using DTM and were asked to rate each benefit using a five-point Likert scale of very low (1), low (2), moderate (3), high (4), and very high (5). Results are displayed in Figure 20.

On average, respondents reported that Easier to Calculate Construction Quantities (SB1) and Earlier Identification of Plan Discrepancies and Conflicts (SB2) are the two project-specific benefits perceived to have high impact. Reducing Risk During Bidding for Contractors and/or DOTs (SB3), Improved Communication on the Project (SB4), Fewer Change Orders or Construction Revisions (SB5), and Fewer Project Delays (SB6) are reported to have a moderate impact on average.

Respondents offered the following additional project-specific benefits:

- Reducing labor needs,
- Improving safety,

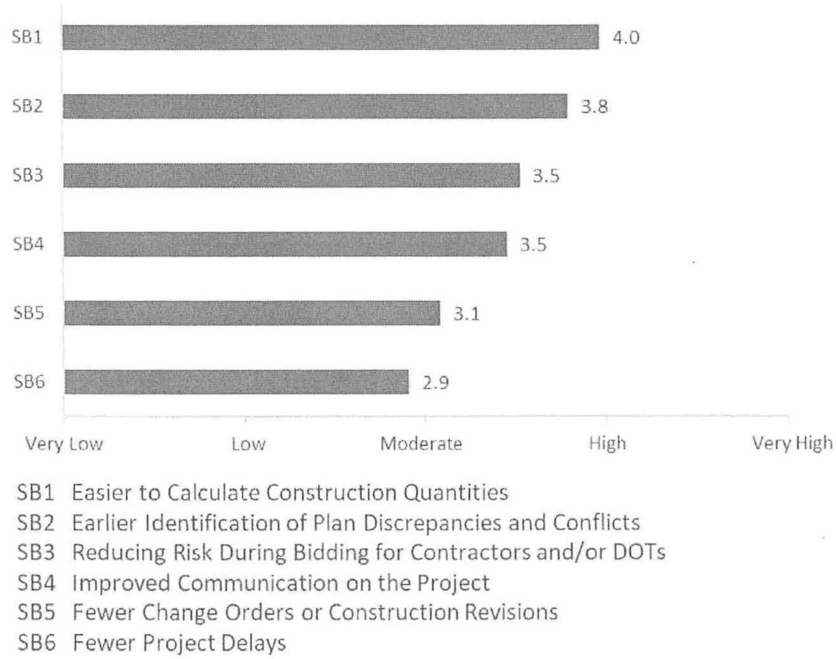


Figure 20. Weighted perception of project-specific benefits of DTM usage, N = 37.

- Performing quantity verifications on contractors' models,
- Performing survey stake-out and grade control,
- Identifying areas in excess materials in right of way, and
- Staging.

3.3.2 DTM Long-Term Benefits

Respondents were asked to indicate their level of agreement with a list of long-term benefits associated with the use of DTMs using a five-point scale of strongly disagree (1), disagree (2), unsure (3), agree (4), and strongly agree (5). Results are displayed in Figure 21.

On average, respondents strongly agreed that Cost Savings (LB1), Improved Accuracy of Plans (LB2), Improved Documentation of Measurements in Database for Future References (LB3), Improved Communication (LB4), and Improved Efficiency of Project Construction (LB5) are long-term benefits that can result from using DTMs. Respondents also agreed, on average, that implementing DTMs can result in Fewer Claims and Litigation (LB6) over the long term. Respondents offered other long-term benefits, including improved time of completion, enhanced construction quality, and less reliance on paper plans.

3.3.3 DTM Hands-On Experience

Respondents were asked to indicate if they had hands-on experience using DTMs on a highway construction project. Of the 38 respondents who answered this question, 58% percent have been directly involved in using DTMs, and the remaining 42% have not directly used a DTM.

Respondents who indicated that they have had hands-on experience using DTMs on a highway construction project were asked to elaborate on their experience and the use of the models.

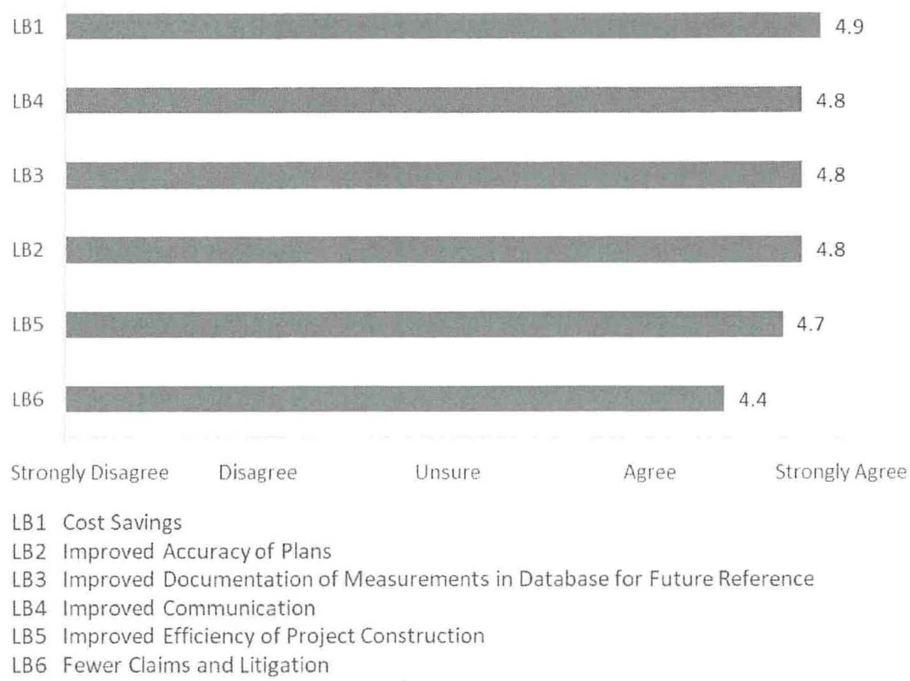


Figure 21. Weighted perception of long-term benefits of DTM usage, N = 38.

Responses are grouped into major and relevant phases for a highway construction project's life cycle and are provided in the following as direct quotes.

- *Design*
  - Developed a DTM to support a new alignment on a multi-bridge project and a 4.5 million cubic yard earthwork project.
  - DTM file was created for quantity calculations and drainage models.
  - DTM experience includes building 3D models.
  - Made sure the specifications were in contract. The Road Construction Engineer went to Peer Exchange in NY and worked hand-in-hand with our designer for the model and with field personnel about implementing it.
  - Designed and modeled four projects that have been built ranging from 2 to 4 million dollars. We do not give the DTMs directly to the contractor, but we give them data pulled from the model.
  - Design uses DTMs to model roadway improvement and compares end area volumes to determine earthwork quantities. The existing and design DTMs are supplied to contractors [. . .] during advertising to assist with their bids.
  - Used DTM mostly during the design phase.
  - Used the existing DTM to create proposed design.
  - Our DOT is in the process of developing a DTM QC/QA policy to be able to hand over the DTM to the contractors. On previous projects, I have provided contractors with the DTM, and the projects were very successful. The key is not necessarily the design DTM, but the existing DTM, with concern of urban reconstruction and so forth. Many times, the existing DTM is not accurate enough for the urban projects that are flat. The key to being successful is the existing DTM, which holds the most accuracy for quantities at the end of the day. Great method on reconstruction of Interstates and in rural areas.

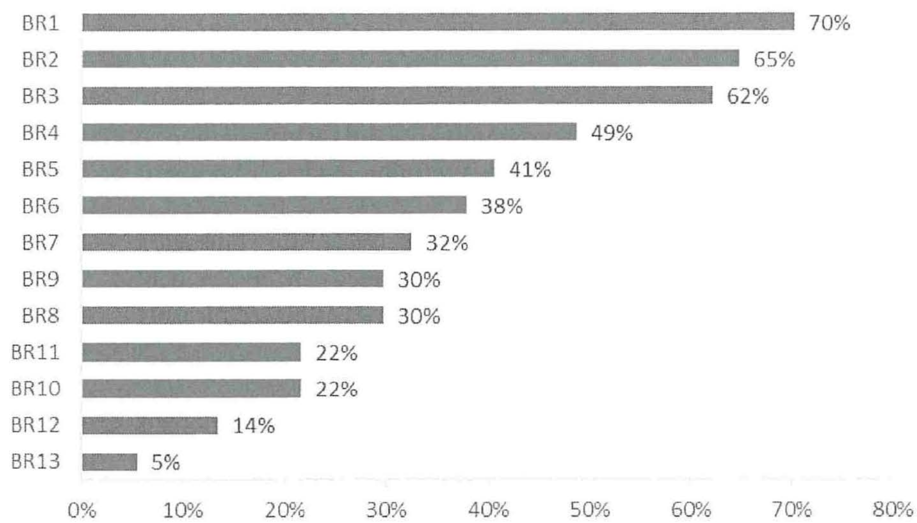
- *Surveying*
  - Our office is responsible for producing DTMs by photogrammetry and LiDAR methods.
  - Have used kinematic equipment to obtain terrain model to determine areal measurements for vegetative establishment quantities.
  - The majority of grading/concrete paving in our state has DTM to be used by the contractor. The plans and x-sections still override any error in the DTMs provided. My involvement has been from doing the construction survey using DTM to creating DTM files to measure for pay.
- *Construction/Maintenance*
  - Contractor used the design DTM files on all construction equipment, including paving operations for grade control. The project was a 12-mile, three-lane freeway concrete rubblization project and HMA [hot-mix asphalt] pavement was raised by minimum of 8 in. at the gutter line with 2.5%, 2%, and 1.5% cross-slopes at crown, which was the far-left lane white stripe between left shoulder and left lane. Left shoulder had a 4% cross slope in the opposite direction. Super elevation was provided on curves. All equipment was set up with computer control with DTM files from servers and run by LAN setup within the 12-mile section of I-295 Interstate. All material requisitions were calculated by the computer, and supplier chain was activated when material was low on proposed work.
  - DTM experience includes providing QC of contractor models; verifying contractor's work using 3D model, staking; building model to QA/QC paper plans, specification; training field staff and field inspectors; and surveying hardware/software procurement and support.
  - Passed on the proposed DTM to construction inspectors to be used for cut and fill, slope verification, and slope limits. The DTM was also passed on to contractor for their use.
  - Provided checks of the design, existing, and as-built DTMs.
  - Used DTM for quantity take off for payment using surface-to-surface comparisons.
  - I was responsible for construction on a $1.1 billion project with multiple uses of DTMs.
  - I have been involved on the inspection side making sure the contractor is building the roadway to the correct elevation and location.

3.3.4 DTM Barriers

From a list of 13 barriers, respondents selected those that impede wider adoption of DTM use on highway construction projects. Figure 22 shows the results. Respondents most frequently cited insufficient knowledge or training for inspectors (DOT or CEI), insufficient knowledge or training for office staff, and insufficient knowledge or training for field survey staff as challenging roadblocks for adopting DTMs. As impediments to DTM adoption by their DOTs, respondents least often indicated that benefits of using DTMs are unknown, that the return on investment (ROI) is unproven, and incompatibility of existing hardware.

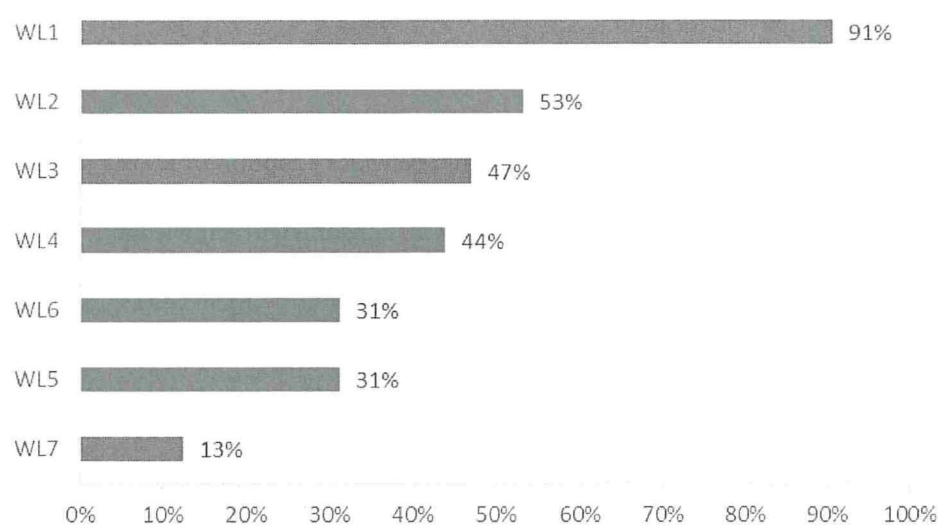
3.4 Legal Aspects

To understand legal implications of DTM usage, the survey asked respondents to specify contractual language within either their DOT's policy manual(s) or the contract documents regarding DTMs used in construction. The survey presented seven categories for this information. Respondents also had an eighth option in case they were not aware of any such contractual language used by their DOT. Actual written DOT policy language is not presented in this report so as not to endorse specific notes, provisions, specifications, or other policy language. Appendix B notes the specific agencies that responded to particular language included in Figure 23. Thus, if one is interested in knowing about policy guidance on file management protocols, the appendix will reference the agencies that may be able to share that information.



BR1 Insufficient knowledge or training for inspectors (DOT or CEI)
BR2 Insufficient knowledge or training for office staff
BR3 Insufficient knowledge or training for field survey staff
BR4 DTMs are often incomplete and inconsistent with contract plans
BR5 Designer fear of problems with DTM/lack of confidence
BR6 Insufficient knowledge or training for equipment operators
BR7 High cost for owner to stay current with field technology using DTMs
BR8 Fear of contractor changing terrain model or introducing error into electronic plan files
BR9 High cost for owner for initial software and hardware
BR10 Inadequacy of IT Infrastructure
BR11 Incompatibility of existing software
BR12 Benefits of using DTMs are unknown. The return on investment (ROI) is unproven.
BR13 Incompatibility of existing hardware

Figure 22. Perceived barriers to implementing DTMs, N = 37.



WL1 DTM (or XML) Provided as "For Information Only" for Contractor to Use at Their Own Risk
WL2 Extent of DOT's Liability for the Accuracy of the DTM
WL3 Survey Practices
WL4 Extent of DOT's Liability for Use of DTM in the Field
WL5 File Management Protocols
WL6 Model Handover Policy from Designer to Contractor
WL7 Plan Production Methods

Figure 23. Written language in DOT contract documents about the use of DTM, N = 36.

Table 1. Contract document precedence when 3D model is included, N = 8.

Document Type	Ranked First	Ranked Second	Ranked Third
Written specifications	88%	12%	0%
2D blueprints	12%	50%	38%
3D models	0%	37%	63%

Although 11% of the respondents indicated that they were not aware of any written specifications related to contractors' use of DTMs, the majority of respondents acknowledged the presence of language related to DTM in their DOT's policy manual(s) or contract documents. Figure 23 shows these results. Among respondent DOTs having written policy manuals or contract documents addressing DTMs, the majority (91%) indicated that the DTM or XML files are supplied as "for information only" for contractors to use at their own risk. About half of the respondents (53%) mentioned that the extent of DOT liability of the accuracy of the DTM is included, and another 47% note that survey practices are included.

Respondents were also asked specific questions about the use of DTM files as a legal contract document. Thirty-eight percent of the respondents indicated that they have not used DTM as a legal document, whereas 24% mentioned that they have. The remainder (38%) have not used DTM as a legal document yet but report that their DOT plans to in the next 1 to 5 years. Additional information on this question can be found in Appendix B.

Respondents affirming that their DOT has used DTM files as a legal document were further asked to rank three contract documents—namely, 2D blueprints, written specifications, and 3D models/DTMs—according to their precedence when a conflict arises. As noted in Table 1, when all three elements were part of the contract documents, most respondents indicated that 3D models ranked third behind written specifications (ranked first) and 2D blueprints (ranked second) when a conflict arose. The 3D model was never the first document of record and had limited use (37%) as the secondary record document.

3.5 Designer/Contractor Interface

This section covers DTM verification and modification processes performed by DOTs.

3.5.1 Verification of DTMs

Only 14% of the respondents indicated that their DOT does not verify the accuracy of DTMs used in construction. Of the respondents who indicated that their DOT has a process to verify models, 78% indicated that they use field verification of survey points, 31% run model checks with the DTM used by the contractor, and 3% compare point cloud data (terrestrial/drone/photogrammetry/LiDAR) to the DTM (as shown in Figure 24). In addition to the options

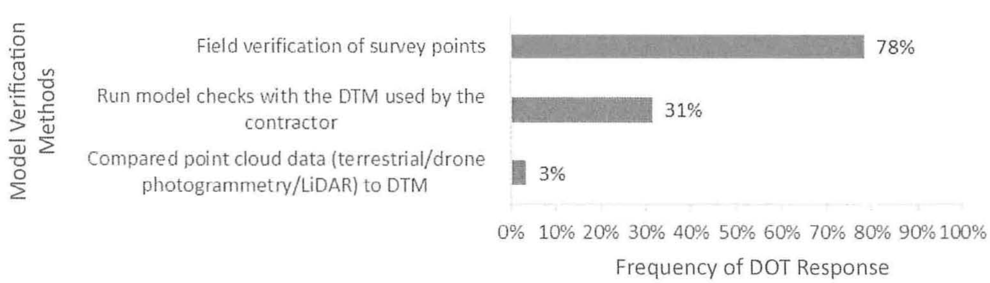


Figure 24. Model verification methods performed by DOTs, N = 32.

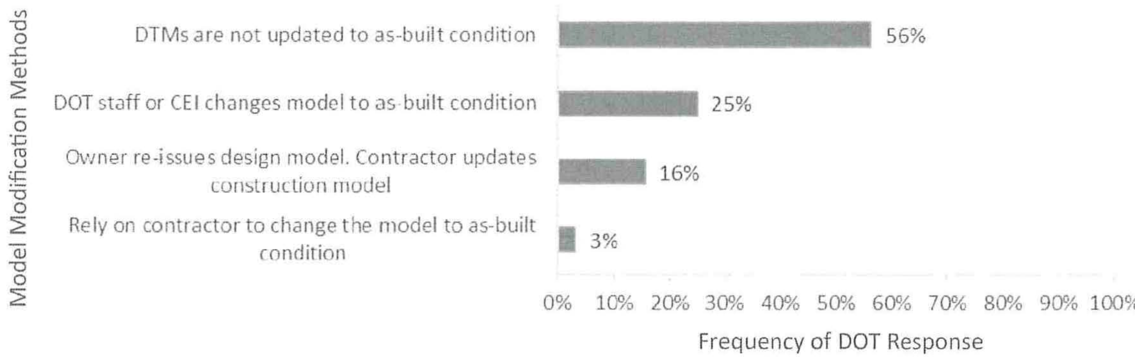


Figure 25. Modification of DTMs as performed by DOTs, N = 32.

provided in the survey, some respondents from South Carolina (SCDOT), Alabama (ALDOT), and North Dakota (NDDOT) indicated that their DOTs perform both field verifications and running model checks with contractors. Montana (MDT) also reported verifying models by performing internal QC checks.

3.5.2 Modification of DTM Models

Respondents were also asked to indicate how models are updated when changes occur in the field. As shown in Figure 25, 56% of the respondents indicated that DTMs are not updated to an as-built condition, but 25% indicated that DOT or CEI personnel change the model to as-built conditions, 16% reported that the owner re-issues the design model and the contractor updates the construction model, and only 3% mentioned that their DOT relies on the contractor to change the model to as-built conditions.

CHAPTER 4

Case Examples

As noted in Chapter 1, follow-up case examples were conducted to gather further details on individual state use and perceptions of using DTMs in construction. The case examples were executed by phone or internet interviews between the research team and selected DOTs. The DOT's survey respondent was contacted to participate in the case example interview and was notified to invite individuals with direct experience with DTMs to participate in the conversation. The semi-structured interviews followed the questions outlined in Appendix C but often drifted toward unique experiences in each state.

Six states were selected as case examples on the basis of their survey responses. Five states were specifically targeted because of their extensive experience with DTMs and, thus, their ability to share lessons learned with other states. One state was selected on the basis of its e-construction and other innovative initiatives but limited use of DTMs in construction. This state would then be able to share reasons for limited use even in a culture of innovation. The following criteria were used to select the experienced case example states:

- Having 10 or more years of experience with DTMs,
- Having used DTMs on 100 or more projects, and
- Having executed a project with the DTM as part of the contract documents.

The five states experienced with DTMs that were interviewed were Maine, Ohio, Oregon, Pennsylvania, and Utah. Despite using DTMs in a relatively limited capacity, Alabama was also interviewed because it is a leader in many technology initiatives. Thus, its feedback was important for understanding some of the barriers and limitations of the technology for continued adoption.

Each agency's interviews are summarized in Table 2 and then detailed in the subsequent subchapters in three distinct sections: benefits/motivation, challenges, and lessons learned.

4.1 Alabama

4.1.1 Benefits/Motivation

The Alabama Department of Transportation (ALDOT) is in its infancy in terms of using DTMs in construction. Its first pilot project was a large grade and drain project, with design finished in the summer of 2016 and construction letting in February 2017. The design, including the proposed DTM, was created in-house. In addition to including the proposed DTM as part of the contract documents, ALDOT used the construction contract to purchase surveying equipment for field staff. Training hours were included to aid DOT staff in verification of the contractor's work. The contract documents included a special provision that was designed to introduce and guide the construction process into further use of the proposed DTM, but it also

Table 2. Summary of case example interviews.

DOT	Benefits	Challenges	Lessons Learned
Alabama	• Calculating quantities • Learning with contractors • Federal aid to assist pilots	• Setting expectations with contractors • Having sizable projects for equipment resource needs	• Communicate early with contractors • Understand capability of contracting community
Maine	• Quick grade checks • Easy quantity comparisons with contractors • Time efficiencies	• Software constantly changing • Legal hurdles (e-signatures, stamps, plan set of record) • Equipment budget	• Peer exchanges help share information with adjacent agencies and contractors they have in common. • Formal training program and frequent updates keep staff ready • E-Construction Implementation team would be beneficial
Ohio	• Enabling stakeless surveying • Time savings • Cost savings • Standardized workflows • Supporting contractors' needs	• Stamping a digital model • Designer concerns with liability • Lack of appropriate training • Lack of standard file formats	• Identify what information the contractor needs • Have support from CADD and Mapping Services–type team
Oregon	• Inspectors found tools that supported their work • Lower surveying costs • Fewer claims and delays over quantities • Quicker and more accurate payments	• Model not yet used as part of the contract documents	• Provide significant, early, statewide training effort • Fully staff Engineering Technology Advancement Unit with IT, design, construction, surveying, and other end users for trial and support
Pennsylvania	• Facilitates AMG • No more "double working" the model	• Compressed construction schedules • Getting quantity measurements with high accuracy during construction	• Have a standard specification for surveying practices and training requirements • Have a group that conducts experimental tests of new technology
Utah	• Supports contractor needs for AMG • Efficient data transfer • Facilitates other emerging technology (unmanned aircraft systems, fully automated machines)	• Leveraging existing software in the field • Surveying equipment costs for field inspectors	• Alternative project delivery methods (CM/GC, DB) maximize benefits. • Require contractors to provide rovers and training

addressed the existing ground terrain model. Active construction is still underway on the pilot project. Contract pay quantities associated with the grade work continue to be verified through field survey before payment is issued. To date, the contractor and ALDOT personnel are aware of no contractor challenges to the as-designed DTM details. As-built information is another requirement of the special provision in place.

ALDOT's initial focus was on projects with large quantities of grade work, so that it, and its contracting community, could get the most benefit from using AMG. It hopes to conduct several more pilot efforts; however, there has not been a significant project with grade work in the state because of budget constraints.

Much of ALDOT's motivation for using DTMs in construction came from attendance at an FHWA EDC-3 Peer Exchange. The road construction engineer for ALDOT's Construction Bureau attended the workshop on using 3D models in construction that was hosted by the New York State Department of Transportation (NYSDOT). The meeting provided confidence and information for ALDOT to begin its first pilot incorporating a special provision that could be included in the construction contract.

Despite some issues with this first pilot project (noted in the next section on challenges), ALDOT is determined to continue. ALDOT realizes that contractors and other agencies are moving in this direction and that now is the time to gain some needed experience.

4.1.2 Challenges

With the strategy of focusing on large-volume grading projects, one roadblock to further use of DTMs in construction is the lack of projects that fit that criterion. The strategy includes procuring equipment for agency inspectors and reimbursing contractors for their expenses in acquiring equipment. For financial reasons, however, ALDOT had to be selective about the size and type of projects for trial. Spending 5%–10% of a project budget on specialized equipment would not be feasible for a pilot effort.

The pilot is still ongoing, but the first two years were particularly challenging. The project was intended to require the contractor and agency to survey daily with GPS and compare data for validation. The contractor, however, did not perform a daily survey for the project, believing that the special provision did not require that effort. The contractor hired a surveying firm to perform monthly surveys, but they were not frequent enough to cover installed work that got covered up before the next monthly survey.

4.1.3 Lesson Learned

The design work was completed in-house, and a consultant is being used for inspection and the fieldwork related to DTM use. The designer of the DTM transitioned to a different office during the project, so he is not available for quick reference. ALDOT found that amending design consultant purchase orders to add the desired DTM deliverables for ongoing designs meant delay and cost that were prohibitive. It also indicated that the additional modeling effort during design may not be appropriate for smaller projects, such as bridge replacements.

ALDOT leveraged several federal resources to help establish the pilot effort. As noted, an FHWA-sponsored peer exchange provided critical knowledge and references to get the project started. ALDOT also used FHWA funds through the State Transportation Innovation Council program to hire a consultant to aid with the specification development, to help acquire equipment, and to use in the project to support the effort.

The process of requiring the contractor to survey, with the agency following closely behind, would have been beneficial to validate the technology as well as to create an opportunity for informal learning. As contractor and agency staff collaborate to create models, they can assist in troubleshooting and sharing effective practices that they can bring back to their respective organizations.

Early communication with the contractor could have improved project outcomes. Issues began at the pre-construction conference when the contractor did not plan to survey as the agency had expected. Despite some experience with AMG, the contractor did not have a significant amount, which may have caused some hesitation. In addition, the contracting community does not appear to use AMG for paving, so the primary benefits for stakeholders using DTMs in construction would still be large grading projects.

4.2 Maine

4.2.1 Benefits/Motivation

Since 2002, the Maine Department of Transportation (MaineDOT) has held an interest in electronic layout and documentation tools. Much of that interest was piqued by advancements made in the contracting community. At about that time, AMG showed up in its projects, which forced the state to figure out the technology so it could properly inspect the work. If contractors were building with digital data, the state needed to be inspecting with digital data. As it learned more about the technology, MaineDOT began to see its value and the future of doing stakeless construction with AMG.

The rollout in Maine was strategic. With a small state budget, convincing leadership of the required investment in the hardware and software was a significant request. To get around this challenge, Maine borrowed contractors' survey equipment and rented other equipment. Job assignments were spread out to areas where the contracting community was more technologically advanced and would be running AMG. Almost all of the state's contractors are now comfortable using AMG and other e-construction tools such as electronic bidding, electronic signatures, and new surveying technologies.

MaineDOT's construction staff members sit on various national and regional committees and participate in tri-state symposiums with New Hampshire and Vermont to learn about the newest technologies. With a smaller geographic footprint, the contracting communities in these northeast states are similar, so these information exchange platforms and shared policy visions are mutually beneficial to the DOTs. They have also seen the impact that one contractor can have on competition when adopting a useful technology.

The most significant benefit for Maine has been the ability to track quantities, in particular earthwork volumes. The ability to take a GPS rover to various points of a project to check grade and detect deviations has resulted in huge time savings with improved data. Grade, centerline, cross-slopes, elevations, and other spatial information can be captured quickly, an outcome that presents a significant upgrade over stringline and grade stakes. The technology makes it easy for MaineDOT staff members to compare quantities to the contractor's quantities. An additional benefit is the amount of surveying support throughout the state. The central office, located in Augusta, provides surveying for the entire state, but regional offices have their own personnel and equipment also. They are ready to help check measurements as available. Maine has one licensed surveyor in the central office as well as one in each of its five regional offices.

Staffing levels are assisted by the technology because inspectors can be more efficient with their time while acquiring the same information previously collected. Further, maintenance gets more accurate location data on assets.

4.2.2 Challenges

The current barrier to further DTM use is MaineDOT's current effort to migrate to OpenRoads Designer (ORD). MaineDOT will have some growing pains adjusting to the differences in the software, but it is still early in the process. Once the system is fully implemented, MaineDOT will have to verify that the 3D plan set meets its needs. Some other states that adopted ORD early had some issues when a software update occurred and caused inoperability issues with their standards.

MaineDOT has a long-term plan to have the 3D model as part of the bid package but must get over some regulatory hurdles on electronic signatures and stamps and on defining what can be a plan set of record. Despite those current issues, the DOT has enough incentive and motivation to overcome them in the near future.

Currently, MaineDOT runs its fieldwork off of the contractor's base station and with contractor equipment or rented equipment. There will be a time when Maine needs to invest in its own equipment and base stations for independent confirmation. The state has a good Continuously Operating Reference Stations Network to survey from but needs its own tools to fully take advantage of that network.

4.2.3 Lesson Learned

The agency began changing its training procedures about 8 to 10 years ago, which involved how to document inspection work electronically while staying within specifications from FHWA. There is no change in the documentation and information, only in how they are captured and presented. Thus, inspectors no longer use field books but now use FieldManager (an AASHTOWare product). Despite some pushback from inspectors in going away from their field books, personnel will adapt as the new system is used and expected more. As noted in the previous subsection, design is moving toward ORD, the most recent Bentley update merging InRoads and Microstation, and MaineDOT is hoping for strong interoperability with construction software like Trimble Business Center (the most-used software of Maine contractors.) Training focuses on how to use the technology, not necessarily on what information is being collected. This approach seeks to keep the traditional skill set of inspectors while blending in the new technology. Poor satellite connections in parts of the state have caused issues locating with base stations; inspectors can overcome technical problems by maintaining their knowledge of conventional methods.

The training is deployed through a typical large meeting, with follow-up one-on-one training as needed. Often, the best way to train has been by field trial. Eventually, most inspectors gain an appreciation for the assistance that technology provides. Some experienced staff members can identify areas that need further checking; for instance, in one project an inspector could tell that measurements using rovers were off. Previous GPS points were in alignment, and no one could understand what the issue was. Eventually, someone figured out that a laborer shoveling snow off the roof of the contractor's trailer was picking up the base station, not knowing what it was, to shovel the snow and then setting it back down. In this situation, old and new training paid off. The experienced inspector with training in traditional methods could tell the data from the rover were wrong. The inexperienced laborer made a critical error that could have caused significant problems and delay if not identified early. As more technology becomes available, field verification and calibration will be critical. But also, importantly, DOT staff still need to visually check and feel empowered to speak up. If the model and rover say a pipe is in the correct place, but one can see that it is not aligned with a stream, then something needs to be done. This is where traditional methods and fundamental training remain essential.

Another lesson learned was to take a similar number of location shots with the GPS rovers as the contractors do. In a project approximately 10 years ago, the contractor and MaineDOT had significant differences in quantities. After some conversations, they realized that the contractor took significantly more data points (in the range of 100 times more), which picked up detailed high and low points. The contractor's surveyors knew to focus their data so that breaks in the terrain were captured. Once DOT personnel followed this method and increased their overall number of points collected, discrepancies were essentially eliminated. Now, the agency and contractor field staff walk the project together and take similar shots.

Although the 2D plan set remains the legal set of record, MaineDOT routinely uses a contract modification to address the contractor's preference for using the 3D model and stakeless surveying. DTM usage can also be a special provision in the contract. At one time, Maine paid plan quantities for yardage bid items. Variations in bidding seemed to indicate that some contractors were exploiting this provision, adjusting their bids through independently performed quantity takeoffs. The state moved to in-place quantity payments in an effort to remove this perception of risk by the contractors. The surveying technology helps facilitate that transition as well.

About a year ago, Maine's Division Directors began holding quarterly meetings to discuss the technology that might aid their asset management responsibilities. DTMs and associated digital information are seen as a cross-divisional subject. Their quarterly meetings are particularly beneficial in exposing various DOT staff members to a range of potential benefits of new available technologies. For example, Maine is distinctly multi-modal, and the DOT's responsibilities for ferry operation are seen as another area in which DTMs might be an efficient tool for asset management.

Finally, a small team that oversees e-construction implementation across all divisions in the agency would help maximize success. Such a group does not currently exist, but construction personnel see the benefit that troubleshooting technologies and addressing policy roadblocks early would have.

4.3 Ohio

4.3.1 Benefits/Motivation

Construction staff members and the agency's contractors pulled the Ohio Department of Transportation (Ohio DOT) into a digital world where DTMs of existing and proposed surfaces are created and shared. Ohio DOT CAD standards have required electronic engineering data as a product of the design phase for some time, but the information was not shared until contractors began requesting it. The state's contractors use the models for estimating quantities, bidding, and machine guidance. A multitude of useful and critical data exist for the construction field. There is more effort in design, which Ohio DOT believes is well offset by the benefits in construction.

Benefits are wide ranging and are anecdotally noted by Ohio DOT. The primary benefits include cost savings, time efficiencies, data consistency, and improved accuracies. Having machine control perform grading tasks saves on surveying, staking, and labor hours involved in grade staking. If contractors can prove the accuracy of their surveying tools and the competency of field staff operators, Ohio DOT permits stakeless surveying practices. The standards, specifications, file formats, and other policies can help provide some consistency in information workflows. In addition, Ohio DOT's Office of CADD and Mapping Services provides a wide range of support services to facilitate effective use of digital design and construction information. It developed a standardized workflow to get design files and digital information efficiently

to contractors during the letting. The previous process required a request of information; now it is standard practice to automatically provide the information.

A pilot project was conducted in which a design consultant modeled grading for earthwork on a project and included it as part of the contract. The project modeling was originally done in Geopak and was later converted to Bentley ORD. Areas of the model that existed but had not been fully developed as part of the grade design were blocked out. In those areas, the proposed model was not contractually binding (for reference only) and could be readily identified by the contractor. The pilot had no significant issues, but its design and quantities were not complicated or significant. Ohio DOT is still capturing feedback from the contractor and has other administration processes (i.e., stamping a 3D model and handling field changes in the model) that need review and approval before it can continue moving the effort forward to get a model in the contract.

Ultimately, construction needs pulled the agency forward; if contractors push for something, it likely has a cost savings or time savings—or both. Ohio DOT expects to implement varying degrees of required complexity within the proposed model information, related to project scope or type. Its inspectors have access to an app that uses location and roadway alignment data for logging photographs. Inspectors also have laptops. Ohio DOT has engaged Bentley to discuss potential tools for inspectors who use the 3D model.

4.3.2 Challenges

While Ohio progresses forward with digital project delivery, it still has several issues to sort out, including stamping a proposed model and designers' concerns with liability. One of the major gaps is in appropriate training and skill development for Ohio DOT staff. Ohio DOT has not conducted formal training focused on reviewing the proposed models delivered from design consultants. Conflicting details occur between the paper plan sets and the electronic engineering data. The agency relies on individual, informal peer training on the equipment and model transfer, primarily because it has resource constraints from both a cost and a time perspective. The previously mentioned CADD and Mapping Services group can assist as needed, but it is not set up for formal training for construction staff. Ohio DOT hopes to improve consistency of the field verification of the proposed model information against sitework. Because the model is not yet part of the contract and contractors use different software than designers do, it is still up to contractors to manage file formatting issues to develop their own proposed model correctly. Ohio DOT has found that contractors often digitize the PDF plan set information they receive.

Ohio DOT notes a variety of other challenges, including having file formats and information needs that are accessible for all project stakeholders; having appropriate skills, equipment, and time to do model verification; rapidly changing mobile device technology; file sizes and file management; connectivity; and modifying daily site inspection practices to include a digital workflow. Ohio DOT is additionally dealing with low staffing levels and a workforce that has little time for training.

4.3.3 Lesson Learned

On the basis of previous technology implementation, Ohio DOT learned to let construction drive what designers do instead of pushing information out to construction. Ohio DOT is in the process of gathering feedback from its construction personnel and contractors about how they consume the data (e.g., how they use proposed models, what level of detail is necessary in the model, and what features need to be modeled). This information, in combination

with some of the workflow challenges noted previously, will help facilitate further use of 3D in construction. This effort is ongoing and in conjunction with the state's contractor association. In addition, the CADD and Mapping Services team has a wiki page with training information and a surveying guide. It also has a monthly webinar to help keep its staff members informed.

4.4 Oregon

4.4.1 Benefits/Motivation

Oregon DOT (ODOT) started its DTM journey in 2011 with a 3D roadway design committee comprising in-house and consultant designers, but the committee had limited construction representation. This committee's objective was to transition all design projects to 3D models as one of the design deliverables. It took almost 5 years to establish, implement, and change contracts to accomplish that objective. In 2015, ODOT began requiring a 3D design model as one of its design deliverables while still having paper plans and typical deliverables for construction (DGN and XML formatted files). ODOT did not share the 3D models with contractors for AMG until 2015. Thus, the 3D initiative was successful until the project got to construction, because there was no construction involvement or a plan for transition to the field.

Eventually, contractors were frustrated by still having to stake and survey, and resident engineers received that message. The state then began formulating plans to share models with contractors so that they could run AMG. Most contractors were building models from paper plans and cross-sections before sharing. The needed change was to allow the contractors' AMG work to replace traditional survey staking. The construction specifications were modified in 2016 to reduce staking when AMG is being used, but ODOT still did not have a good way to check the work in the engineer offices. Many early challenges included the following: Most construction offices did not have the surveying tools and equipment for inspection; there was very little CADD or 3D design knowledge in the construction offices; the state was concerned that, without the proper tools or training, the models would be useless for its construction staff. Further, ODOT needed to be sure it had sufficient time and resources to get its construction personnel up to speed.

The first effort was providing inspectors with GPS tools to use on their projects. It began as a pilot effort in three regional construction offices that could mobilize quickly. The inspectors received two 8-hour basic trainings on opening files, checking the model, using the equipment, and so on. Centralized surveying support was provided, and group emails helped keep everyone up to date while the modernization effort was under way. Then, over the course of the next 2 years, procedures, construction workflows, and other policy changes were made to enable field use of DTMs. The changes included changing forms, adding and modifying specifications, and providing guidance on inspectors' diaries. ODOT encountered roadblocks along the way, but a bottom-up approach allowed end users to assist in rapidly addressing issues and to guide the methodology to suit their needs. Around 2018, the goal of equipping every construction office with hardware, software, and personnel training was achieved. Oregon's centralized technology group maintains a high profile, offering training and communicating at construction inspector seminars. The model workflow has been enabled from design through construction project close and final payments for all projects.

ODOT's inspection staff members were highly receptive to the changes. Experienced inspectors found that the new tools supported the high-quality work they were already doing. Contractors are significant beneficiaries of the changes as well. At bid, 80% or better models are issued, which reduces their estimating risks. After bid, 99% complete models lower surveying costs through AMG. In general, contractors more consistently achieve their smoothness bonuses. One project

saw a 30% schedule savings through model use. Contractors that were early adopters had a competitive edge because of the efficiencies gained, which also put added pressure on the competition and hastened ODOT's move toward digital delivery.

The state also benefits from reduced claims and arguments over quantities, and leaders believe it is because they can verify plan quantity bid payments. The 3D models, AMG, and global navigation satellite system (GNSS) tools have reduced the variance in what the contractor calculates, what the agency calculates, and what the plan quantity/bid item states. Now everyone gets the same answer because everyone is using the same data. With faster, field-verified quantity measurements, payments occur more quickly and accurately. The model workflow also creates transparency between the DOT and the contracting community.

DOT construction staff have enjoyed additional benefits from the innovation occurring in their field offices. Going from flip phones and adding machines to GPS and digital plans raised abilities, skills, and, significantly, staff morale.

4.4.2 Challenges

The last major step for ODOT toward fully digital project delivery is mandating the use of DTMs and 3D models by adding them as part of the contract documents. Although models are created and shared for every project with significant earthwork, adding them to the contract documents with precedence over plans would be a logical next step. The eBIDS handoff package and construction survey handoff package are required on all state and federal aid Statewide Transportation Improvement Program roadway projects designated to 3R or 4R standards. This requirement applies to projects located on the state highway system, regardless of whether the project is delivered by ODOT, a local agency, or a consultant. Any exception to this requirement must have written approval from the region roadway manager no later than the Advance Plans project delivery milestone, as described in the Highway Design Manual. ODOT inspectors rely, however, on the model as a field verification tool during inspection, so it makes sense that there is not a current push for adding the model to the contract at this time. The model already holds a secure role in supporting contract management and oversight efforts.

4.4.3 Lesson Learned

Without skilled field staff, the process would have significant challenges and inefficiencies that could doom the effort. Thus, one of ODOT's first noteworthy initiatives was to provide training at construction offices, which was a major undertaking. After the local pilots, training was conducted at every construction office. To even access the hardware, an 8-hour training course was required. Regional training was then offered on an as-needed basis or as updates occurred with hardware and software. In addition, at any training session for inspectors or any other formal meeting, quick updates were provided while also allowing for the inspection staff members to provide feedback. Contractors are required to share any digital information they intend to put to use on a project. The concept of sharing information frequently helped keep lines of communication open and reinforced the importance of using these tools effectively.

ODOT also staffs an Engineering Technology Advancement Unit with individuals from IT, design, construction, surveying, and other end users of engineering technology. These individuals are tasked with identifying emerging technologies, evaluating their feasibility for use, and assisting in implementation and training. Thus, as issues arose, ODOT operations personnel had access to the Engineering Technology Advancement Unit to help troubleshoot solutions, and they then distributed their new knowledge throughout the state.

4.5 Pennsylvania

4.5.1 Benefits/Motivation

The Pennsylvania Department of Transportation (PennDOT) has an agencywide goal to go completely digital by 2025 through all phases of a project. The initiative, Digital Delivery 2025, envisions that construction projects will be bid using 3D technology and will no longer be in a traditional plan format. Some projects are exempt, such as guide rail, pavement marking, crack sealing, and bridge preservation.

Although recently unveiling this initiative, the agency has been using 3D information since the mid-1990s with surveying and photogrammetry. The initial significant transition was for designers who could visualize and understand 3D survey data but had always produced 2D plan sheets as their product. Thus, they were not completely comfortable sharing models with contractors. Contractors received only 2D plans (in PDF); they would then survey, occasionally use LiDAR, create their own models, and use AMG to build. PennDOT personnel refer to this cycle as "double working"—when the 3D design model is discarded and then recreated. Starting in 2013, districts and design consultants were allowed to share 3D models for information only. Digital Delivery 2025 will ultimately produce complete models for contractors. Designer training is under way and nearing completion.

The biggest driver for PennDOT's use of DTMs is AMG. Using machine guidance offers significant time and cost savings, workflow efficiencies, and improved accuracies. The state's contractors have used AMG and 3D models for so long that it is difficult for them to remember managing projects without those resources. By moving to this technology early and with the ambitious goals for 2025, the state actively investigates new technologies. It was an early tester of terrestrial and mobile LiDAR as well as unmanned aerial systems (UASs). Having the resources and willingness to try emerging technologies gives PennDOT an advantage of effectively leveraging new tools and technology earlier to capture better data more quickly.

4.5.2 Challenges

One initial challenge for PennDOT was the lack of available time in the construction phase of projects for its personnel to become familiar with the surveying technology. PennDOT's surveying experts had early involvement with design staff through ground surveys, photogrammetry, LiDAR, and other products used in design. Their involvement gave them time and familiarity needed to build confidence in the technology. When construction needs survey information, it is often a critical item, but the in-house surveying group is not set up for quick turnaround.

Quantity measurements are still a challenge for PennDOT. Its surveying office has experimented with UASs and other reality modeling technologies to create a DTM to represent intermediate construction conditions. These solutions are not ideal for serious design applications; however, they are able to get quick data on quantities and changes in earthwork. Pennsylvania currently has a steering committee and pilot efforts to use UASs for quantity measurement. During the current coronavirus pandemic (spring 2020), the UASs have been useful as a social distancing tool for construction inspection. The ultimate goal would be to verify payments to contractors with these quantities using a DTM, because contractors are still traditionally paid by truck load.

4.5.3 Lessons Learned

PennDOT's construction specifications are issued through Publication 408. Section 686 of this publication outlines construction surveying procedures and refers to processes for

surveying with AMG. It includes a provision that inspectors and field staff should receive 2 days (8 hours each) of training on the equipment, tying into benchmarks, loading the models, and using models for AMG; the training includes a Q&A session. The inspectors and field staff receive a second 1-day, 8-hour training refresher for every additional year that equipment is in use.

One additional lesson learned noted by PennDOT relates to its surveying technology experimental tests. When a new technology has the potential for use in the state, a ground truth exercise is conducted (location of 5–20 points compared to traditional survey points). The results of this test are used to guarantee repeatable results to give confidence in the technology itself.

4.6 Utah

4.6.1 Benefits/Motivation

The culture in the Utah DOT (UDOT) has resulted in an innovative attitude best described as "not being afraid to fail in the interest of trying things out." UDOT has had continuous administrative leadership for 20 years, resulting in a consistent message and shared vision for experimenting with and using technology. There is no roadblock of having to prove ROI for emerging technologies; rather, there is a trust within the DOT to explore and make appropriate decisions on potential use.

UDOT's journey with DTMs began with AMG for paving and earthwork. It was a contractor-driven effort, because contractors came to the agency describing a need to build models to run the new equipment. The close, trusting relationship between the agency and its contractors facilitated this request, so UDOT had little hesitation sharing the design model with contractors. Partnering has also been an intentional and integral part of UDOT's culture. The strong relationship between the agency and the contracting community allows for technology trials. The culture of innovation stirred up some thoughts within UDOT, which began to investigate putting the models in the contract, working toward fully digital project delivery, and getting rid of paper documentation altogether. The vision to go digital led to a standard way of thinking when evaluating current procedures and a realization that many processes involved capturing original information, stripping it of certain data, and then, at best, sharing what was left for another party to rebuild—which is inefficient, redundant, and costly.

This initiative was assisted by a robust DB program in the state that fortuitously began decades ago. In 1990, Utahns decided to strongly pursue a bid for the Winter Olympic Games and approved tax revenues to support construction of the necessary infrastructure. They hoped to land the 1998 or 2002 Winter Olympic Games, so this infrastructure was needed quickly. Utah state legislators drafted and signed legislation allowing for the DB delivery method to facilitate the compressed timeline. Thus, UDOT has many years of experience with DB that bridges the gap between design and construction and helps build collaboration and confidence in the DTM tools and technology. The traditional design-bid-build delivery method may lead to some hesitation by contractors to use a model provided for information only.

Although DB enabled the early, rapid adoption of DTMs in construction, the first projects that used 3D design in construction were CM/GC arrangements. The CM/GC process gives an opportunity for risk to be discussed early with contractors. These alternative project delivery methods brought designers, contractors, and the DOT together early in the projects to discuss the specific model-based needs of the contractors. Such methods put an additional workload on designers to develop more complete designs that don't leave much for contractors to decipher, but any increase in engineering/design hours is easily offset by earlier clash detection of typical field issues. UDOT has seen a dramatic decrease in contractor claims along with the intrinsic

benefit of having contractors understand what goes into project design and the design process. A shared, mutual understanding of the work involved helps both parties gain an appreciation and collaborative attitude toward project delivery. Because the design estimator and construction superintendent need different information from the digital design, post-construction debriefings are beneficial and should be done as early as possible.

Specific benefits seen by UDOT include the efficiency in data transfer with AMG and building confidence in design that facilitates model use in asset management. A comprehensive model is critical to UDOT's long-term goal of moving away from paper documentation and toward digital information. Further, the agency can position itself to take advantage of emerging technologies such as UASs and fully automated machines only if a DTM and 3D design are ready. Not only does the technology need to be proven and ready but the human skills also need to be developed and prepared. Moving construction and asset management tasks to model-based processes pushes the technology into the hands of employees and away from traditional paper documentation.

4.6.2 Challenges

An issue for UDOT has been leveraging existing software packages for maximum benefit in the field. The design software packages are fantastic for the design phase of projects, but the models are difficult to consume in the field without laptops and the relevant software package. The field viewer tools need improvement. As DOTs run into software concerns, it would be beneficial to document and share those with service providers, given the market share that DOTs represent. To avoid these issues, where possible, UDOT still uses 2D data through Esri and geographic information system software. A software-agnostic approach is needed to meet the demands and requirements of DOT work.

Surveying equipment for inspectors is expensive, so a low-cost solution would enable increased use. It will also be important for attracting future generations to work for the DOT. New technologies such as UASs, DTMs, and AMG provide more sophistication to the roles and responsibilities of field staff.

4.6.3 Lesson Learned

UDOT stopped doing its own surveying about 20 years ago (for design and construction) and placed those responsibilities with contractors. In the process, the agency lost an immense amount of surveying knowledge. With the capabilities afforded through DTMs, construction and inspection staff need to develop those surveying skills again. The leap in surveying skills for inspectors from plans to models is significant, so states that do most of their own surveying may have an advantage from a knowledge and skills standpoint.

A contractor intending to use AMG must provide GPS rover(s) for inspection and training on the chosen proprietary system, whether it's Trimble, Topcon, or another provider. Data collected by the survey are sent to the designers, who verify that the shots in the field match the model. The verification process is not critical, however, because inspectors still take core samples, measure thicknesses, require smoothness, and take other QA steps.

Contracting method plays a huge part in facilitating workflows with DTMs. CM/GC, DB, and progressive DB all present advantages by promoting a stronger relationship between the designer and contractor. The traditional contractual relationships in design-bid-build can interfere with their dialogue and sharing of information.

CHAPTER 5

Summary of Findings

The primary objective of this synthesis study was to document current processes and strategies for the effective use and transfer of DTMs from design into the construction phase of highway projects. Secondary objectives were to identify DOTs that have experience using DTMs in construction and to provide an overview of implementation to date and lessons learned that identify success factors and challenges.

Each objective was previously addressed in the survey results presented in Chapter 3 and the DOT case examples described in Chapter 4. The following sections revisit the primary findings of this NCHRP synthesis study. The information used to generate the conclusions is inclusive of the 40 DOTs that responded to the survey. When specific numbers are referenced, non-responding states are not included in the findings.

5.1 Extent of DTM Use in Construction and Inspection

- Although 3D modeling and DTMs have been around for some time, their use is still inconsistent nationally: 15% of DOTs use DTMs on fewer than 10 projects annually, whereas 25% of DOTs use DTMs on more than 100 projects (Figure 9, N = 40). The results are further echoed in length of use: 11% of DOTs have less than 3 years of experience whereas 45% of DOTs have more than 10 years of experience (Figure 10, N = 40).
- States have used DTMs most on corridor widening, intersection improvement, bridge construction or replacement, and road rehabilitation projects (Figure 18, N = 37). The larger the project budget, the more likely a DTM was used. In fact, only 5% of states have used a DTM on a project with a budget of less than $1 million. Over half (51%) of responding DOTs use DTMs on all projects regardless of project budget (Figure 17, N = 37).
- A few states outsource their DTMs for all projects; a few others create them all in-house. For most states, in-house model creation ranges between 40% and 60% (Figure 11, N = 32).
- Frequency of use in construction inspection varies also: 10% of DOTs never use DTMs in inspection, 24% rarely use them, 42% sometimes use them, and 24% often use DTMs when inspecting projects (Figure 14, N = 38). No survey respondent believed that his or her agency always uses a DTM during inspection. As noted in its case example in Chapter 4, PennDOT seeks to go fully digital through all phases of a project's life cycle through its Digital Delivery 2025 initiative.
- In the construction phase of projects, most DOTs use their DTMs for grade work (95%), quantity measurements (94%), survey verification (92%), field staking (89%), AMG (86%), and progress checks (86%). Essentially, agencies primarily use DTMs for geospatial field measurements. Fewer DOTs use the models for future activities such as work planning (49%) and cost analysis for maintenance (31%) (Figure 12, N = 38). In Chapter 4, ALDOT, MaineDOT, ODOT, PennDOT, and UDOT note that their contracting communities' use of

AMG pushed them forward to adopting and using DTMs in construction. That exposure and subsequent use stirred a vision for several agencies toward a future with reduced or no paper documentation on projects.

5.2 Policy Guidance for DTM Use

- Although some states have significant experience with DTMs in both number of projects and length of use, little policy guidance is formally documented. The most frequently noted written specification language is that the DTM (or XML) is provided as "for information only" for contractors to use at their own risk (91%). Even for some advanced states outlined in the case examples, the final remaining hurdle to full digital project delivery is moving the model into the contract documents. There is a significant drop-off to the next most frequent policy language. The extent of DOT liability for the accuracy of the model (53%), standard surveying practices (47%), and extent of DOT liability for the use of the model in the field (44%) are the next most frequently documented policy statements. Less than a third (31%) of states describe file management protocols or model handover policy from design to construction. (Figure 23, N = 36).
- Contract document precedence remains in the typical order, with written specifications having priority over 2D plans and 3D models. Given that most states still do not include 3D models in contract documents, this finding is not surprising but could be changing in the near future. Although 38% of DOTs have not executed a project for which the DTM was part of the legal contract documents, they state that they plan to in the near future because the use of 3D models is increasing, and states are becoming more open to using 3D models as a legal contract document. Only 24% of states have executed a project with the 3D model included in the contract documents (N = 32). Additional information can be found in Appendix B.

5.3 Model Verification Processes

- In the field, most states verify accuracy of the work built from the model by conducting independent verification of survey points (78%). Less than a third of states (31%) run actual model checks with the design model and the model used by the contractor. A few states conduct both field verification of survey points and model checks. One state mentioned that it compares point cloud data captured from either LiDAR or UAS photogrammetry to the contractor's DTM (Figure 24, N = 32). In Chapter 4, MaineDOT notes the importance of similar location and number of survey points for model verification. If those vary significantly, it can lead to significant discrepancies between agency and contractor quantities.
- If changes are made in the field, however, few states actually modify the DTM model once the contractor is using it. More than half of the states surveyed do not have the DTMs updated to an as-built condition; 25% of DOTs have their staff or consultant inspection staff keep the model updated as an as-built. A select few states have the designer or contractor make the as-built modifications of the DTM (Figure 25, N = 32).

5.4 Benefits and Strategies for Effective DTM Use in Construction

- In the short term, DOTs believe that the most significant benefits that DTMs provide in construction are easier calculation of quantities, earlier identification of conflicts, reduced risk during bidding, and improved communication among project stakeholders. In general, states also believe that DTMs lead to fewer change orders and project delays (Figure 20, N = 37).

In the case examples, the DOTs noted the time savings and accuracies achieved for quantity measurement as meaningful benefits, along with the ability to support their contractors' use of AMG.

- DOTs were more strongly aligned with their vision of long-term benefits from DTM use. Those long-term benefits noted were cost savings, improved accuracy of plans, improved documentation of measurements, improved communication, better efficiency in construction, and fewer claims and litigation (Figure 21, N = 38). Some noteworthy reductions in claims were mentioned in Chapter 4, particularly in the cases of MaineDOT, ODOT, and UDOT.
- The successes discussed in the case examples seemed to be attributed to three main sources; supportive leadership, resource dedication, and collaborative contracting relationships. UDOT noted the importance of stable leadership that champions technology and educated risk-taking. Its administrative leadership has been relatively consistent for 20 years and is not afraid to fail with well-planned trials. From a resource standpoint, ODOT has dedicated staff comprising IT and end users to evaluate, test, implement, and support technology initiatives. There are proponents in MaineDOT for a similar group. PennDOT has an active surveying group that evaluates and supports emerging technologies. Finally, all DOTs reported positive relationships with their contracting partners and the importance of trust in those relationships.
- Training is always an issue with any new or emerging technology in regard to how successful its implementation is. This area appears to have a wide range of strategies and approaches. Most states (84%) rely on informal peer training for their end users. Some also provide field-based (65%) or classroom-based (52%) training with hardware and software. Almost a third (32%) of states just provide reference material and rely on the end users to develop their own skills (Figure 15, N = 37). MaineDOT offers classroom style training but also one-on-one in the field training as needed. ODOT conducted training at every construction office in the state. It also requires an 8-hour training course before staff members can access surveying equipment. Regional training is offered on an as-needed basis or as updates occur. PennDOT has 2-day training requirements on technical and procedural issues. Several DOTs also mentioned benefits of these advanced skillsets not only in efficiency of work but also in attracting a future workforce. Working with 3D models, UASs, and GPS technology leads to a more sophisticated workforce and one that is positioned to attract younger generations.

5.5 Challenges and Knowledge Gaps

- Even with numerous benefits and the examples of states with significant experience, many barriers remain to further use and implement DTMs. Training presents the most consistent roadblock for DOTs. Specifically, training for inspectors (70%), office staff (65%), and field survey staff (62%) are the most frequently mentioned barriers for further DTM use in construction. Other frequently noted issues are incomplete and inconsistent models (49%), designer lack of confidence in the model (41%), insufficient knowledge of equipment operators (38%), and cost of staying current with field technology (32%) (Figure 22, N = 37).
- On the basis of the case examples, some more specific challenges emerged. DOTs have some uncertainty regarding newly available software. The transition to a new platform has a learning curve that should enhance workflows, but the DOTs interviewed are not there yet. In addition, some of the existing field software packages can struggle with complex models. Equipment costs can be an impediment and a difficult sell depending on budgets and decision makers in the DOT. Some states are also still struggling to overcome certain regulatory and legal issues such as accepting electronic stamps and electronic signatures, and defining the makeup of a plan set of record.

The findings from this synthesis project demonstrate some inconsistencies in the use of DTMs in construction. DOTs have a wide range of experience in both the number of projects and the years of experience with DTMs. The case examples suggest that the states with innovative, risk-seeking cultures related to technology adoption and collaborative relationships with their contracting communities seemed to be the most advanced in their use of DTMs in construction. Often, the contracting community pulled those states forward: contractors' adoption of AMG forced their partner states to investigate the models driving the equipment. In addition, states with higher use of alternative contracting methods such as DB and CM/GC found it easier to share the design model in the construction phase because of early contractor involvement. Training and skillsets are barriers to further use of DTMs in construction. Some DOTs lack well-developed training programs for their end users, while others lack the in-house surveying knowledge to effectively leverage the models in construction.

Ultimately, the next major advancement in DTM use in construction for the DOTs surveyed and interviewed is to incorporate the models into contract documents. A select few states have successfully integrated models into contract documents. Most have not but do have near-term aspirations to do so, whereas others still have no interest in including the model in the contract. For those DOTs working toward that integration, adopting necessary policy changes, training needs, and hardware and software costs (both initial and maintenance costs) seem to be the current focus. Finally, as noted in the MaineDOT case example, if contractors are going to build DOT projects digitally, then inspection tasks can also be done digitally.

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APPENDIX A

Survey Questionnaire

Email to Potential Participants

From: NCHRP Staff

To: Members of AASHTO Standing Committee on Construction

Subject: NCHRP Project 20-05/Synthesis Topic 51-01: Practices for Construction-Ready Digital Terrain Models

Dear AASHTO Committee on Construction (COC) Member,

Hope you had a safe and wonderful holiday season and Happy New Year! The Transportation Research Board (TRB), through the National Cooperative Highway Research Program (NCHRP), under the sponsorship of the American Association of State Highway and Transportation Officials (AASHTO), and in cooperation with the Federal Highway Administration (FHWA) is preparing a synthesis report on Practices for Construction-Ready Digital Terrain Models.

The purpose of this questionnaire is to identify state DOT use, evaluation, and perceptions of DTMs in the construction of highway projects. The results of the survey will be incorporated into a synthesis of highway practice, with the intent of helping DOTs evaluate and improve their DTM practices.

This survey is being sent to each state DOT's voting member of the AASHTO COC for distribution to applicable employees. **If you are not the appropriate person at your agency to complete this questionnaire, please forward this request to the correct person.** A PDF copy of the survey is attached to see the questions to help determine who is best to take the electronic survey.

Please compete and submit this survey by January 24, 2020. We estimate that it should take no more than 30 minutes to complete. If you have any questions or problems with operation or access to the questionnaire, please contact me, the project principal investigator, Dr. Gabe Dadi, at (859) 257-5416 or gabe.dadi@uky.edu.

Please complete the survey at the following link, https://uky.az1.qualtrics.com/jfe/form/SV_b8W3qHz4S1OILNr, by Friday, January 24th.

Thank you for your time and cooperation in support of this important project. Your cooperation in completing this survey will help ensure the success of the effort.

Best,

Gabriel B. Dadi, Ph.D., PE
W. L. Raymond and R. E. Shaver Chair Associate Professor
Department of Civil Engineering
University of Kentucky

DTM Survey Questionnaire

NCHRP Synthesis 51-01: Digital Terrain Models for Construction

NCHRP SYNTHESIS Project 20-05/Topic 51-01
PRACTICES FOR CONSTRUCTION-READY DIGITAL TERRAIN MODELS QUESTIONNAIRE

Dear AASHTO Committee on Construction (COC) Member,

The Transportation Research Board (TRB), through the National Cooperative Highway Research Program (NCHRP), under the sponsorship of the American Association of State Highway and Transportation Officials (AASHTO), and in cooperation with the Federal Highway Administration (FHWA) is preparing a synthesis report on Practices for Construction-Ready Digital Terrain Models. The purpose of this questionnaire is to identify state DOT use, evaluation, and perceptions of DTMs in the construction of highway projects. The results of the survey will be incorporated into a synthesis of highway practice, with the intent of helping DOTs evaluate and improve their DTM practices. This survey is being sent to each state DOT's voting member of the AASHTO COC for distribution to applicable employees. **If you are not the appropriate person at your agency to complete this questionnaire, please forward this request to the correct person. Please compete and submit this survey by January 24, 2020.** We estimate that it should take no more than 30 minutes to complete. If you have any questions or problems with operation or access to the questionnaire, please contact me, the project principal investigator, Dr. Gabe Dadi, at (859) 257-5416 or gabe.dadi@uky.edu. Thank you for your time and expertise in completing this questionnaire.

Please identify your contact information below. Your contact information will be kept confidential. This is strictly for follow-up purposes.

- ○ Name: ________________________________
- ○ Title: ________________________________
- ○ Email: ________________________________
- ○ Phone Number: ________________________________

What department of transportation (DOT) do you work for?

- ○ Alabama
- ○ Alaska
- ○ Arizona
- ○ Arkansas
- ○ California
- ○ Colorado
- ○ Connecticut
- ○ Delaware
- ○ District of Columbia
- ○ Florida
- ○ Georgia
- ○ Hawaii
- ○ Idaho
- ○ Illinois
- ○ Indiana
- ○ Iowa
- ○ Kansas
- ○ Kentucky
- ○ Louisiana

- ◯ Maine
- ◯ Maryland
- ◯ Massachusetts
- ◯ Michigan
- ◯ Minnesota
- ◯ Mississippi
- ◯ Missouri
- ◯ Montana
- ◯ Nebraska
- ◯ Nevada
- ◯ New Hampshire
- ◯ New Jersey
- ◯ New Mexico
- ◯ New York
- ◯ North Carolina
- ◯ North Dakota
- ◯ Ohio
- ◯ Oklahoma
- ◯ Oregon
- ◯ Pennsylvania

- Rhode Island
- South Carolina
- South Dakota
- Tennessee
- Texas
- Utah
- Vermont
- Virginia
- Washington
- West Virginia
- Wisconsin
- Wyoming

What division do you work for within your agency?

- Highway Design
- CADD/Support
- Surveying/Support
- Construction
- Other ____

How would you best describe your role in the agency?

- ◯ Field Engineer/Inspector
- ◯ Construction Engineer/Engineer Manager
- ◯ Materials Engineer/Technician
- ◯ CADD/Technical Support
- ◯ Designer
- ◯ Other ____

Approximately how many projects use DTMs in a year in your organization?

- ◯ Less than 10
- ◯ 10–50
- ◯ 50–100
- ◯ More than 100

Estimate how many years your DOT has been using DTMs on construction projects.

- ◯ 0–1 years
- ◯ 1–3 years
- ◯ 3–5 years
- ◯ 5–7 years
- ◯ 7–10 years
- ◯ 10+ years

How frequently do you use DTMs in the construction inspection process?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Often
- ○ Always

Indicate the source of DTMs used on your state's construction projects with your best estimation:

	0 10 20 30 40 50 60 70 80 90 100
% created in-house	
% created by an outside consultant	

How has your state transportation agency used DTMs in projects? Please indicate one response for each.

	Never	Rarely	Sometimes	Often	Always
Field Staking	○	○	○	○	○
Progress Checks	○	○	○	○	○
Quantity Measurements	○	○	○	○	○
Automated Machine Guidance	○	○	○	○	○
Grade Work	○	○	○	○	○
Pavement Thickness Checks (Including Aggregate Base Courses)	○	○	○	○	○
QA/QC, Clash Detection, or Reducing Plan Discrepancies	○	○	○	○	○
Cost Analysis for Initial Construction Bid	○	○	○	○	○
Cost Analysis for Future Maintenance	○	○	○	○	○

Work Planning, Productivity, or Efficiency	○	○	○	○	○
Survey Verification	○	○	○	○	○
Other	○	○	○	○	○

What DTM training is provided to the construction inspection staff in your state? Please check all that apply.

- ☐ Field-based training on hardware and software
- ☐ Classroom-based training on hardware and software
- ☐ Only provided reference materials (hard copy or electronic)
- ☐ Informal, peer training
- ☐ No training provided
- ☐ Other ____

Page Break

Please evaluate the following aspects of DTMs that are handed over to contractors for their use on projects **based on the perspective of the DOT.**

	Very Low	Low	Moderate	High	Very High	Not Applicable
Accuracy compared to PDF/printed (contract) plan information	○	○	○	○	○	○
Level of detail (level of precision between the model's 3D geometry and real world)	○	○	○	○	○	○
Quality or completeness	○	○	○	○	○	○
Overall added value of DTM	○	○	○	○	○	○
Interoperable format (or usefulness of data format)	○	○	○	○	○	○

Please evaluate the following aspects of DTMs that are handed over to contractors for their use on projects **based on the perspective of contractors (as perceived by the DOT).**

	Very Low	Low	Moderate	High	Very High	Not Applicable
Accuracy compared to PDF/printed (contract) plan information	○	○	○	○	○	○
Level of detail (level of precision between the model's 3D geometry and real world)	○	○	○	○	○	○
Quality or completeness	○	○	○	○	○	○
Overall added value of DTM	○	○	○	○	○	○
Interoperable format (or usefulness of data format)	○	○	○	○	○	○

Page Break

What size projects do you use DTMs for (based on engineer's estimate of cost)? Please check all that apply.

- ☐ All projects regardless of size
- ☐ $0–$1 million
- ☐ >$1 million – $5 million
- ☐ >$5 million – $20 million
- ☐ >$20 million

What types of projects have you used DTMs for? Please check all that apply.

- ☐ Road Resurfacing
- ☐ Road Rehabilitation
- ☐ Intersection Improvement
- ☐ Corridor Widening
- ☐ Bridge Rehabilitation
- ☐ New or Replacement Bridge
- ☐ Safety Improvement (shoulder widening, rumble stripe, pavement marking/markers, guardrail projects with minimal design, etc.)
- ☐ Other ____

What project delivery methods have you used DTMs with? Please check all that apply.

- ☐ Design-Bid-Build
- ☐ Design-Build
- ☐ Construction Management (CM)/General Contractor (GC)
- ☐ Public-Private Partnership (P3)
- ☐ Integrated Project Delivery (IPD)
- ☐ Other ____

For projects using DTMs, who was responsible for construction inspection?

- ○ DOT Staff
- ○ Construction and Engineering Inspection (CEI) Consultant
- ○ Other ____

Have you been directly involved in using DTM on a highway construction project?

- ○ Yes
- ○ No

Please provide a brief description of your involvement in using DTMs on highway construction projects. (This question is optional.)

____

____

____

____

____

Please rate the project-specific benefits of using the DTM, in terms of the following areas.

	No Benefit	Very Low	Low	Moderate	High	Very High
Reduced Risk During Bidding for Contractors and/or DOTs	○	○	○	○	○	○
Fewer Change Orders or Construction Revisions	○	○	○	○	○	○
Fewer Project Delays	○	○	○	○	○	○
Earlier Identification of Plan Discrepancies and Conflicts	○	○	○	○	○	○
Improved Communication on the Project	○	○	○	○	○	○
Easier to Calculate Construction Quantities	○	○	○	○	○	○
Other	○	○	○	○	○	○

Considering long-term benefits of DTM use across DOTs, please state the level of agreeableness with the following statements. Please indicate one response for each.
Long-term use of DTMs across the DOT will lead to...

	Strongly Disagree	Disagree	Agree	Strongly Agree	Unsure
Improved Accuracy of Plans	○	○	○	○	○
Improved Efficiency of Project Construction	○	○	○	○	○
Improved Communication	○	○	○	○	○
Cost Savings	○	○	○	○	○
Fewer Claims and Litigation	○	○	○	○	○
Improved Documentation of Measurements in Database for Future Reference	○	○	○	○	○
Other	○	○	○	○	○

What barriers exist for adoption or further implementation of DTMs on highway construction projects? Please check all that apply.

- ☐ DTMs are often incomplete and inconsistent with contract plans
- ☐ Insufficient knowledge or training for office staff
- ☐ Insufficient knowledge or training for field survey staff
- ☐ Insufficient knowledge or training for equipment operators
- ☐ Insufficient knowledge or training for inspectors (DOT or CEI)
- ☐ High cost for owner for initial software and hardware
- ☐ High cost for owner to stay current with field technology using DTMs
- ☐ Benefits of using DTMs are unknown. The return on investment (ROI) is unproven.
- ☐ Incompatibility of existing hardware
- ☐ Incompatibility of existing software
- ☐ Inadequacy of information technology (IT) infrastructure
- ☐ Designer fear of problems with DTM/lack of confidence
- ☐ Fear of contractor changing terrain model or introducing error into electronic plan files
- ☐ Other ____

What is included in the written language of your DOT's policy manual(s)/contract document that the contractor is bound to, regarding the DTMs used in construction? Please check all that apply.

- ☐ File management protocols
- ☐ Survey practices
- ☐ Plan production methods
- ☐ Model handover policy from designer to contractor
- ☐ DTM (or XML) provided as "for information only" for contractor to use at his/her own risk
- ☐ Extent of DOT's liability for the accuracy of the DTM
- ☐ Extent of DOT's liability for use of DTM in the field
- ☐ To my knowledge, no policy manual documents DTM practices
- ☐ Other ______________________________

Has your DOT executed a project that included a DTM as a legal contract document?

- ○ Yes
- ○ No, but plan to in the near future. Please explain: ______________________________
- ○ No, and have no plans to.

Place in order from top to bottom with the document taking precedence placed at the top when a conflict arises.

______ 2D blueprints
______ Written specifications
______ 3D model/DTM

How has your state verified the accuracy of the DTM used in construction?

- ○ Run model checks with the DTM used by the contractor
- ○ Field verification of survey points
- ○ No verification steps are taken
- ○ Compared point cloud data (terrestrial/drone photogrammetry/LiDAR) to DTM
- ○ Other ____

End of Block: Default Question Block

Start of Block: Block 1

When changes occur in the field, how is the model modified? Please check all that apply.

- ☐ Rely on contractor to change the model to as-built condition
- ☐ DOT staff or CEI changes model to as-built condition
- ☐ Owner re-issues design model. Contractor updates construction model
- ☐ DTMs are not updated to as-built condition
- ☐ Other ____

APPENDIX B

Survey Results

Use Cases:

The following tables show the distribution of DOT responses for each use case in the survey.

Grade Work	Count	DOT
Never	2	Rhode Island, Minnesota
Rarely	4	South Carolina, Alabama, Texas, Indiana
Sometimes	8	Oregon, Illinois, Montana, Oklahoma, North Carolina, Connecticut, Maine, New Mexico
Often	17	Utah, Virginia, Florida, Arkansas, Nebraska, North Dakota, Alaska, Ohio, Iowa, Nevada, Michigan, Idaho, West Virginia, Missouri, Delaware, Colorado, Kentucky
Always	6	New Hampshire, Wisconsin, New Jersey, Wyoming, Washington, Mississippi

Quantity Measurements	Count	DOT
Never	2	Rhode Island, Minnesota
Rarely	8	Utah, New Jersey, South Carolina, Nebraska, Alabama, Michigan, Texas, Kentucky
Sometimes	14	Wisconsin, Illinois, Montana, Florida, North Carolina, North Dakota, Ohio, Iowa, Nevada, Maine, Missouri, New Mexico, Indiana, Colorado
Often	9	Oregon, New Hampshire, Virginia, Arkansas, Alaska, Connecticut, Idaho, West Virginia, Mississippi
Always	3	Wyoming, Washington, Delaware

Survey Verification	Count	DOT
Never	3	Rhode Island, Utah, Minnesota
Rarely	7	New Hampshire, Pennsylvania, Montana, Nebraska, Alabama, Texas, Kentucky
Sometimes	9	Wisconsin, Illinois, South Carolina, Wyoming, North Carolina, Maine, Missouri, Indiana, Colorado
Often	16	Oregon, Virginia, Arkansas, Oklahoma, North Dakota, Alaska, Ohio, Iowa, Nevada, Michigan, Connecticut, Idaho, Washington, West Virginia, Delaware, New Mexico
Always	3	Florida, New Jersey, Mississippi

Field Stacking	Count	DOT
Never	4	Rhode Island, Ohio, Connecticut, Minnesota
Rarely	8	Utah, South Carolina, Nebraska, Alabama, Idaho, Maine, New Mexico, Indiana
Sometimes	10	Virginia, Illinois, Montana, Florida, Arkansas, Nevada, Missouri, Texas, Colorado, Kentucky
Often	10	Oregon, Wisconsin, North Carolina, North Dakota, Alaska, Iowa, Michigan, Washington, West Virginia, Delaware
Always	4	New Hampshire, New Jersey, Wyoming, Mississippi

Automated Machine Guidance	Count	DOT
Never	5	Rhode Island, Arkansas, Connecticut, Texas, Minnesota
Rarely	5	Virginia, South Carolina, Alabama, Idaho, Indiana
Sometimes	7	Oregon, Illinois, Nebraska, North Dakota, Washington, New Mexico, Colorado
Often	17	Utah, Pennsylvania, Montana, Florida, Wyoming, North Carolina, Alaska, Ohio, Iowa, Nevada, Michigan, Maine, West Virginia, Missouri, Mississippi, Delaware, Kentucky
Always	3	New Hampshire, Wisconsin, New Jersey

Progress Checks	Count	DOT
Never	5	Rhode Island, North Carolina, Idaho, New Mexico, Minnesota
Rarely	12	Utah, Illinois, Arkansas, New Jersey, Nebraska, Alabama, North Dakota, Nevada, Maine, Texas, Indiana, Kentucky
Sometimes	11	New Hampshire, Virginia, Montana, Florida, South Carolina, Wyoming, Alaska, Michigan, Washington, Missouri, Colorado
Often	7	Oregon, Wisconsin, Ohio, Iowa, Connecticut, West Virginia, Delaware
Always	1	Mississippi

Cost Analysis for Initial Construction Bid	Count	DOT
Never	9	Rhode Island, New Jersey, South Carolina, Nebraska, Alabama, North Carolina, Texas, Minnesota, Kentucky
Rarely	8	Oregon, Utah, New Hampshire, Florida, Michigan, Connecticut, Mississippi, Indiana
Sometimes	10	Virginia, Illinois, Montana, North Dakota, Alaska, Iowa, Nevada, Maine, West Virginia, Colorado
Often	6	Wisconsin, Pennsylvania, Arkansas, Ohio, Missouri, New Mexico
Always	4	Wyoming, Idaho, Washington, Delaware

QA/QC, Clash Detection, or Reducing Plan Discrepancies	Count	DOT
Never	10	Rhode Island, New Jersey, Nebraska, North Carolina, North Dakota, Ohio, Texas, New Mexico, Indiana, Minnesota
Rarely	10	Oregon, New Hampshire, Alabama, Michigan, Idaho, Maine, West Virginia, Mississippi, Delaware, Kentucky
Sometimes	13	Utah, Wisconsin, Virginia, Illinois, Montana, South Carolina, Wyoming, Alaska, Iowa, Nevada, Connecticut, Washington, Colorado
Often	4	Florida, Arkansas, Oklahoma, Missouri

Pavement Thickness Checks	Count	DOT
Never	11	Rhode Island, Utah, Arkansas, South Carolina, Wyoming, North Carolina, Connecticut, Missouri, Texas, Indiana, Minnesota
Rarely	10	Oregon, Virginia, Montana, Nebraska, Alabama, North Dakota, Iowa, Michigan, West Virginia, New Mexico
Sometimes	9	Wisconsin, Illinois, Alaska, Ohio, Idaho, Maine, Delaware, Colorado, Kentucky
Often	5	New Hampshire, Florida, Nevada, Washington, Mississippi
Always	1	New Jersey

Work Planning Productivity, or Efficiency	Count	DOT
Never	18	Oregon, Rhode Island, Utah, New Hampshire, Montana, New Jersey, South Carolina, Nebraska, Alabama, North Carolina, Ohio, Iowa, Michigan, West Virginia, Texas, Indiana, Minnesota, Kentucky
Rarely	7	Illinois, North Dakota, Nevada, Connecticut, Idaho, Maine, Colorado
Sometimes	5	Wisconsin, Virginia, Arkansas, Washington, Delaware
Often	4	Florida, Alaska, Mississippi, New Mexico
Always	1	Wyoming

Cost Analysis for Future Maintenance	Count	DOT
Never	24	Oregon, Rhode Island, Utah, New Hampshire, Wisconsin, Montana, Florida, Arkansas, New Jersey, South Carolina, Wyoming, Nebraska, Alabama, North Carolina, North Dakota, Iowa, Michigan, Idaho, West Virginia, Texas, New Mexico, Indiana, Minnesota, Kentucky
Rarely	9	Virginia, Illinois, Ohio, Nevada, Connecticut, Washington, Maine, Mississippi, Colorado
Sometimes	2	Alaska, Delaware

DTM Training Provided to Construction Inspection Staff:

The following tables show the distribution of DOT responses for each type of training offered to construction inspection staff.

Informal, Peer Training	Count	DOT
Not selected	11	Rhode Island, Utah, Oklahoma, New Jersey, Nevada, Maine, Missouri, Delaware, New Mexico, Indiana, Minnesota
Selected	26	Oregon, New Hampshire, Wisconsin, Virginia, Illinois, Montana, Florida, Arkansas, South Carolina, Wyoming, Nebraska, Alabama, North Carolina, North Dakota, Alaska, Ohio, Iowa, Michigan, Connecticut, Idaho, Washington, West Virginia, Mississippi, Texas, Colorado, Kentucky

Field-Based Training on Hardware and Software	Count	DOT
Not selected	17	Rhode Island, New Hampshire, Wisconsin, Virginia, Oklahoma, Nebraska, North Dakota, Ohio, Iowa, Idaho, West Virginia, Texas, Delaware, New Mexico, Indiana, Colorado, Minnesota
Selected	20	Oregon, Utah, Illinois, Montana, Florida, Arkansas, New Jersey, South Carolina, Wyoming, Alabama, North Carolina, Alaska, Nevada, Michigan, Connecticut, Washington, Maine, Missouri, Mississippi, Kentucky

Classroom-Based Training on Hardware and Software	Count	DOT
Not selected	21	Rhode Island, Utah, New Hampshire, Wisconsin, Montana, Oklahoma, New Jersey, Nebraska, North Carolina, North Dakota, Ohio, Iowa, Nevada, Idaho, West Virginia, Texas, Delaware, New Mexico, Indiana, Minnesota, Kentucky
Selected	16	Oregon, Virginia, Illinois, Florida, Arkansas, South Carolina, Wyoming, Alabama, Alaska, Michigan, Connecticut, Washington, Maine, Missouri, Mississippi, Colorado

Only Provided Reference Materials (hard copy or electronic)	Count	DOT
Not selected	27	Oregon, Rhode Island, Utah, New Hampshire, Wisconsin, Virginia, Montana, Arkansas, Oklahoma, New Jersey, Wyoming, Nebraska, North Dakota, Alaska, Ohio, Iowa, Nevada, Michigan, Connecticut, West Virginia, Missouri, Texas, Delaware, New Mexico, Indiana, Colorado, Minnesota
Selected	10	Illinois, Florida, South Carolina, Alabama, North Carolina, Idaho, Washington, Maine, Mississippi, Kentucky

No Training Provided	Count	DOT
Selected	5	Rhode Island, Oklahoma, Delaware, New Mexico, Minnesota

DTM Barriers:

The following tables show the distribution of DOT responses for each barrier in the survey.

Insufficient Knowledge or Training for Inspectors (DOT or CEI)	Count	DOT
Not selected	11	Utah, Pennsylvania, Wyoming, Iowa, Connecticut, Idaho, Washington, Missouri, Mississippi, Colorado, Minnesota
Selected	26	Oregon, Rhode Island, New Hampshire, Wisconsin, Virginia, Illinois, Montana, Florida, Arkansas, New Jersey, South Carolina, Nebraska, Alabama, North Carolina, North Dakota, Alaska, Ohio, Nevada, Michigan, Maine, West Virginia, Texas, Delaware, New Mexico, Indiana, Kentucky

Insufficient Knowledge or Training for Office Staff	Count	DOT
Not selected	13	Utah, Montana, Wyoming, Nebraska, Nevada, Washington, Maine, West Virginia, Missouri, Mississippi, Texas, Colorado, Minnesota
Selected	24	Oregon, Rhode Island, New Hampshire, Wisconsin, Virginia, Illinois, Pennsylvania, Florida, Arkansas, New Jersey, South Carolina, Alabama, North Carolina, North Dakota, Alaska, Ohio, Iowa, Michigan, Connecticut, Idaho, Delaware, New Mexico, Indiana, Kentucky

Insufficient Knowledge or Training for Field Survey Staff	Count	DOT
Not selected	14	Utah, Pennsylvania, Florida, Arkansas, Wyoming, Alabama, Iowa, Idaho, Washington, West Virginia, Mississippi, Texas, Colorado, Minnesota
Selected	23	Oregon, Rhode Island, New Hampshire, Wisconsin, Virginia, Illinois, Montana, New Jersey, South Carolina, Nebraska, North Carolina, North Dakota, Alaska, Ohio, Nevada, Michigan, Connecticut, Maine, Missouri, Delaware, New Mexico, Indiana, Kentucky

DTMs Are Often Incomplete and Inconsistent with Contract Plans	Count	DOT
Not selected	19	Oregon, Utah, New Hampshire, Montana, Florida, Arkansas, New Jersey, South Carolina, Wyoming, Alabama, Alaska, Ohio, Iowa, Idaho, Missouri, Texas, Indiana, Minnesota, Kentucky
Selected	18	Rhode Island, Wisconsin, Virginia, Illinois, Pennsylvania, Nebraska, North Carolina, North Dakota, Nevada, Michigan, Connecticut, Washington, Maine, West Virginia, Mississippi, Delaware, New Mexico, Colorado

Designer Fear of Problems with DTM/ Lack of Confidence	Count	DOT
Not selected	22	Oregon, Rhode Island, Utah, New Hampshire, Wisconsin, Florida, Arkansas, New Jersey, Wyoming, Nebraska, Iowa, Michigan, Idaho, West Virginia, Missouri, Mississippi, Texas, Delaware, New Mexico, Colorado, Minnesota, Kentucky
Selected	15	Virginia, Illinois, Pennsylvania, Montana, South Carolina, Alabama, North Carolina, North Dakota, Alaska, Ohio, Nevada, Connecticut, Washington, Maine, Indiana

Insufficient Knowledge or Training for Equipment Operators	Count	DOT
Not selected	23	Oregon, Utah, Pennsylvania, Montana, Florida, Arkansas, Nebraska, Alabama, North Carolina, Ohio, Iowa, Michigan, Idaho, Washington, Maine, West Virginia, Missouri, Mississippi, Texas, Indiana, Colorado, Minnesota, Kentucky
Selected	14	Rhode Island, New Hampshire, Wisconsin, Virginia, Illinois, New Jersey, South Carolina, Wyoming, North Dakota, Alaska, Nevada, Connecticut, Delaware, New Mexico

High Cost for Owner to Stay Current with Field Technology Using DTMs	Count	DOT
Not selected	25	Utah, New Hampshire, Wisconsin, Pennsylvania, Montana, Florida, Arkansas, New Jersey, Nebraska, North Carolina, Alaska, Ohio, Iowa, Michigan, Idaho, Washington, Maine, West Virginia, Missouri, Mississippi, Delaware, New Mexico, Colorado, Minnesota, Kentucky
Selected	12	Oregon, Rhode Island, Virginia, Illinois, South Carolina, Wyoming, Alabama, North Dakota, Nevada, Connecticut, Texas, Indiana

Fear of Contractor Changing Terrain Model or Introducing Error into Electronic Plan Files	Count	DOT
Not selected	26	Oregon, Rhode Island, Utah, New Hampshire, Wisconsin, Montana, Florida, Arkansas, Wyoming, Nebraska, Alabama, North Dakota, Alaska, Iowa, Michigan, Connecticut, Idaho, Washington, West Virginia, Missouri, Texas, Delaware, Indiana, Colorado, Minnesota, Kentucky
Selected	11	Virginia, Illinois, Pennsylvania, New Jersey, South Carolina, North Carolina, Ohio, Nevada, Maine, Mississippi, New Mexico

High Cost for Owner for Initial Software and Hardware	Count	DOT
Not selected	26	Utah, New Hampshire, Wisconsin, Pennsylvania, Montana, Florida, New Jersey, Nebraska, North Carolina, North Dakota, Alaska, Iowa, Nevada, Michigan, Connecticut, Idaho, Washington, Maine, West Virginia, Missouri, Mississippi, Delaware, New Mexico, Colorado, Minnesota, Kentucky
Selected	11	Oregon, Rhode Island, Virginia, Illinois, Arkansas, South Carolina, Wyoming, Alabama, Ohio, Texas, Indiana

Inadequacy of Information Technology (IT) Infrastructure	Count	DOT
Not selected	29	Oregon, Rhode Island, Utah, New Hampshire, Wisconsin, Pennsylvania, Arkansas, New Jersey, Wyoming, Nebraska, Alabama, North Carolina, North Dakota, Ohio, Iowa, Nevada, Michigan, Connecticut, Washington, Maine, West Virginia, Missouri, Mississippi, Texas, Delaware, New Mexico, Colorado, Minnesota, Kentucky
Selected	8	Virginia, Illinois, Montana, Florida, South Carolina, Alaska, Idaho, Indiana

Incompatibility of Existing Software	Count	DOT
Not selected	29	Rhode Island, Utah, New Hampshire, Wisconsin, Illinois, Pennsylvania, Montana, Florida, Arkansas, New Jersey, Wyoming, Nebraska, Alabama, North Dakota, Alaska, Ohio, Iowa, Nevada, Connecticut, Idaho, Washington, West Virginia, Missouri, Mississippi, Texas, New Mexico, Colorado, Minnesota, Kentucky
Selected	8	Oregon, Virginia, South Carolina, North Carolina, Michigan, Maine, Delaware, Indiana

Incompatibility of Existing Hardware	Count	DOT
Not selected	35	Oregon, Rhode Island, Utah, New Hampshire, Wisconsin, Illinois, Pennsylvania, Montana, Florida, Arkansas, New Jersey, Wyoming, Nebraska, Alabama, North Carolina, North Dakota, Alaska, Ohio, Iowa, Nevada, Michigan, Connecticut, Idaho, Washington, Maine, West Virginia, Missouri, Mississippi, Texas, Delaware, New Mexico, Indiana, Colorado, Minnesota, Kentucky
Selected	2	Virginia, South Carolina

Benefits of Using DTMs Are Unknown. The Return on Investment (ROI) Is Unproven.	Count	DOT
Not selected	32	Oregon, Utah, New Hampshire, Wisconsin, Virginia, Illinois, Pennsylvania, Montana, Arkansas, New Jersey, South Carolina, Wyoming, Nebraska, Alabama, North Carolina, North Dakota, Alaska, Ohio, Iowa, Nevada, Michigan, Connecticut, Washington, West Virginia, Missouri, Mississippi, Texas, Delaware, New Mexico, Indiana, Colorado, Minnesota
Selected	5	Rhode Island, Florida, Idaho, Maine, Kentucky

Written Language in Contracts:

The following tables show the distribution of DOT responses for the contractual language.

To My Knowledge, No Policy Manual Documents DTM Practices.	Count	DOT
Not selected	31	Oregon, Utah, New Hampshire, Wisconsin, Virginia, Illinois, Pennsylvania, Florida, Arkansas, New Jersey, South Carolina, Wyoming, Nebraska, Alabama, North Carolina, North Dakota, Alaska, Ohio, Iowa, Nevada, Michigan, Connecticut, Idaho, Washington, West Virginia, Missouri, Mississippi, Texas, Delaware, Colorado, Kentucky
Selected	5	Rhode Island, Montana, New Mexico, Indiana, Minnesota

DTM (or XML) Provided as "For Information Only" for Contractor to Use at His/Her Own Risk	Count	DOT
Not selected	7	Rhode Island, Montana, Wyoming, Alaska, New Mexico, Minnesota, Kentucky
Selected	29	Oregon, Utah, New Hampshire, Wisconsin, Virginia, Illinois, Pennsylvania, Florida, Arkansas, New Jersey, South Carolina, Nebraska, Alabama, North Carolina, North Dakota, Ohio, Iowa, Nevada, Michigan, Connecticut, Idaho, Washington, West Virginia, Missouri, Mississippi, Texas, Delaware, Indiana, Colorado

Extent of DOT's Liability for the Accuracy of the DTM	Count	DOT
Not selected	19	Rhode Island, New Hampshire, Wisconsin, Virginia, Pennsylvania, Montana, Arkansas, South Carolina, North Carolina, Alaska, Ohio, Michigan, Connecticut, Idaho, Missouri, Delaware, Indiana, Minnesota, Kentucky
Selected	17	Oregon, Utah, Illinois, Florida, New Jersey, Wyoming, Nebraska, Alabama, North Dakota, Iowa, Nevada, Washington, West Virginia, Mississippi, Texas, New Mexico, Colorado

Survey Practices	Count	DOT
Not selected	21	Rhode Island, New Hampshire, Wisconsin, Virginia, Pennsylvania, Montana, Arkansas, South Carolina, Nebraska, North Dakota, Nevada, Connecticut, Washington, Missouri, Texas, Delaware, New Mexico, Indiana, Colorado, Minnesota, Kentucky
Selected	15	Oregon, Utah, Illinois, Florida, New Jersey, Wyoming, Alabama, North Carolina, Alaska, Ohio, Iowa, Michigan, Idaho, West Virginia, Mississippi

Extent of DOT's Liability for Use of DTM in the Field	Count	DOT
Not selected	22	Rhode Island, New Hampshire, Wisconsin, Virginia, Pennsylvania, Montana, Arkansas, South Carolina, Wyoming, Alabama, North Carolina, Ohio, Nevada, Michigan, Connecticut, Idaho, Missouri, Texas, Delaware, Indiana, Minnesota, Kentucky
Selected	14	Oregon, Utah, Illinois, Florida, New Jersey, Nebraska, North Dakota, Alaska, Iowa, Washington, West Virginia, Mississippi, New Mexico, Colorado

Model Handover Policy from Designer to Contractor	Count	DOT
Not selected	26	Rhode Island, Utah, New Hampshire, Virginia, Illinois, Pennsylvania, Montana, Arkansas, South Carolina, Nebraska, North Carolina, Alaska, Ohio, Iowa, Connecticut, Idaho, Washington, Missouri, Mississippi, Texas, Delaware, New Mexico, Indiana, Colorado, Minnesota, Kentucky
Selected	10	Oregon, Wisconsin, Florida, New Jersey, Wyoming, Alabama, North Dakota, Nevada, Michigan, West Virginia

Plan Production Methods	Count	DOT
Not selected	32	Oregon, Rhode Island, Utah, New Hampshire, Wisconsin, Virginia, Pennsylvania, Montana, Arkansas, New Jersey, South Carolina, Wyoming, Nebraska, Alabama, North Carolina, Alaska, Ohio, Iowa, Nevada, Connecticut, Idaho, Washington, West Virginia, Missouri, Mississippi, Texas, Delaware, New Mexico, Indiana, Colorado, Minnesota, Kentucky
Selected	4	Illinois, Florida, North Dakota, Michigan

As for using DTM as a legal document, the following DOTs either did not reply or did not use DTM as a legal document.

Using DTM as a Legal Document	DOT
No reply	Oklahoma, Georgia, Kansas
DOTs that do not use DTM as a legal document	Rhode Island, New Hampshire, New Jersey, South Carolina, Nebraska, North Carolina, Ohio, Connecticut, Maine, West Virginia, Missouri, Texas, Colorado, Minnesota
DOTs that do not use DTM as a legal document but are planning to	Oregon, Wisconsin, Virginia, Illinois, Pennsylvania, Montana, Arkansas, Nevada, Washington, Mississippi, Delaware, New Mexico, Indiana, Kentucky
DOTs that use DTM as a legal document	Utah, Florida, Wyoming, Alabama, North Dakota, Alaska, Iowa, Michigan, Idaho

The following table shows more details on DOTs that do not use DTM as a legal document, but are planning to in the future (NA means the DOT did not provide details).

DOTs That Do Not Use DTM as a Legal Document but Are Planning To	
Oregon	Note sure, model is included but may be as reference only at this time
Wisconsin	Under consideration
Virginia	Currently looking for the appropriate project to initiate
Illinois	NA
Pennsylvania	Department Initiative of Digital Delivery in 2025
Montana	maybe in a year or two
Arkansas	I assume we are moving in that direction, but I don't have knowledge of changes.
Nevada	New Microstation OpenRoads ultimate goal is to hand off 3D design surfaces to bid/build.
Washington	plan to include terrain models in next engineering software platform

Mississippi	NA
Delaware	We are working on giving model to contractor as a supplement to the plans. Targeting May 2020.
New Mexico	NA
Indiana	We are wanting to move to this in the future as we can implement, but we are probably talking 3 to 5 years from now.
Kentucky	Unsure if this has been discussed

As for DOTs that used DTM as a legal document, they ranked it in precedence to written specifications and 2D drawings in case of a legal dispute. Results are shown in the table below (NA means the DOT did not provide a ranking).

DOTs That Use DTM as a Legal Document, and Their Corresponding Ranking of Documents That Take Precedence	
Utah	Rank 1: Written specifications Rank 2: 3D model Rank 3: 2D drawings
Florida	Rank 1: Written specifications Rank 2: 2D drawings Rank 3: 3D model
Wyoming	NA
Alabama	Rank 1: Written specifications Rank 2: 3D model Rank 3: 2D drawings
North Dakota	Rank 1: Written specifications Rank 2: 2D drawings Rank 3: 3D model
Alaska	Rank 1: Written specifications Rank 2: 2D drawings Rank 3: 3D model

Iowa	Rank 1: 2D drawings Rank 2: Written specifications Rank 3: 3D model
Michigan	Rank 1: Written specifications Rank 2: 3D model Rank 3: 2D drawings
Idaho	Rank 1: Written specifications Rank 2: 2D drawings Rank 3: 3D model

APPENDIX C

Case Example Questions

NCHRP Synthesis 51-01 ***Practices for Construction-Ready Digital Terrain Models***

Follow-Up Phone Interview Questions

1. Describe your DTM journey (i.e., when did it start, what barriers did you encounter/how did you overcome them).
2. What training is provided to the construction staff and construction inspection staff in your state to use DTMs?
3. What benefits have you seen from using DTMs in construction?
4. What could enable your state to use DTMs in construction more?
5. Has your DOT executed a project that included a DTM as a legal contract document? Describe the decision-making process that led to your response.
6. If your contractors use a DTM for machine control or any other purposes, how do you ensure their model is equivalent to the designer's DTM?
7. What suggestions do you have for lessons learned related to handing over the DTM to contractors?

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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